Large-Scale Archaeological Prospection of Early Modern Battlefields:

Geophysical Surveys at the Battlefield of Waterloo

Duncan Williams

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Abstract

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This thesis considers the role of large-scale minimally-invasive prospection methods for the archaeological investigation of early modern battlefields. This is explored using the Napoleonic battlefield of Waterloo, Belgium (1815) as a case study. Methodological focus is on the use of near-surface geophysical methods measuring electromagnetic soil properties (primarily frequency-domain electromagnetic induction and magnetometry). To date, geophysical methods have been applied in only a limited fashion on early modern conflict sites and typically not at the landscape scale required for the investigation of these expansive sites. Battlefield archaeology is a relatively recent sub-discipline which faces methodological challenges due to the extremely ephemeral nature of the evidence that these sites hold. These challenges are, however, not wholly unique and the work undertaken here is more broadly applicable to other types of archaeology involving subtle traces of the past. The work begins by carefully reviewing the relevant range of targets and the associated geophysical properties enabling their detection, which influences the choice of instrumentation. Next, geophysical datasets from Waterloo are considered, alongside information derived from a programme of invasive sampling, to evaluate the archaeological information provided by the large-scale prospection and suggest perspectives on future use. A parallel line of work considers a minimally-invasive workflow for the mapping of colluvial (eroded) soil deposits at Waterloo, which greatly influence the preservation and detectability of archaeological deposits of interest. Soil erosion in arable landscapes represents one of the most significant threats to archaeological sites around the world; thus, this aspect is broadly relevant. In all, this work demonstrates the insights provided by the application of non-invasive prospection methods at early modern battlefield sites, while emphasizing some of the ongoing challenges associated with detecting extremely subtle archaeological traces in palimpsest landscapes.

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Author’s Declaration

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This Integrated Thesis includes material that has been or will be submitted for publication. This material has been edited for better coherence within the thesis. Details are included at the outset of each chapter. The author of the thesis was the primary author on all submitted publications, having sole responsibility for writing the original manuscripts. Listed co-authors contributed to the reviewing of drafts and overall direction of the research.

Abbreviations

AWaP – Agence Wallonne du Patrimoine

BOA – bottom-of-atmosphere

Bt – textural B-horizon

DOE – depth of exploration

EC – electrical conductivity

ECa – apparent electrical conductivity

EM - electromagnetic

EMI – electromagnetic induction

ERT – electrical resistivity tomography

EVI – Enhanced Vegetation Index

FDEM – frequency-domain electromagnetic induction

FM – fluxgate magnetometry

GPR – ground penetrating radar

HCP – horizontal coplanar coil pair

IB – induction balance (or inductively balanced)

IDW – inverse distance weighting (interpolation method)

IP – in-phase (FDEM response)

L8 – Landsat-8

LIN – Low Induction Number

LiDAR – Light Detection and Ranging

MS – magnetic susceptibility

MSa – apparent magnetic susceptibility

MSJ – Mont-Saint-Jean

msu – magnetic susceptibility units

NDVI – Normalized Difference Vegetation Index

NN – natural neighbour (interpolation method)

PI – pulse induction

PRP – perpendicular coil pair

QP – quadrature-phase (FDEM response)

S2 – Sentinel-2

SR – surface reflectance

TOA – top-of-atmosphere

UAV – uncrewed aerial vehicle

USLE – Universal Soil Loss Equation

UXO – unexploded ordnance

VCP – vertical coplanar coil pair

VLF – very low frequency

Chapter 1: Introduction

The Changing Scale and Nature of Archaeological Research

Archaeologists are now routinely investigating increasingly large landscapes, making use of a range of prospection techniques for the identification of evidence related to human occupation and environmental dynamics (Darvill et al. 2013; Trinks et al. 2018, 2022; De Smedt et al. 2022). The continued development and sophistication of non-invasive methods, primarily in near-surface geophysics, has been in large part responsible for this, allowing for the efficient investigation of archaeological landscapes on a scale that was not possible merely a couple decades ago (Trinks 2015). These methods identify contrasts in physical properties measured by sensors at some distance from a buried target (Gaffney and Gater 2003; Garré et al. 2023). Some of these contrasts relate to anthropogenic objects or features of interest, which can then be selectively sampled in various ways to derive traditional archaeological data.

Such methods allow for efficient investigation of sites that cannot be approached using traditional prospection methods, and this is particularly useful where the density of objects and features of interest is relatively low. While a range of site types fall under this category, this research focuses on the application of large-scale geophysical prospection methods to a specific type of archaeological landscape: those that represent the archaeology of relatively recent conflict events. Until recently the primary domain of historians, there is now an entire sub-discipline of battlefield archaeology that focusses on the study of material remains of past conflicts to provide insights that cannot be obtained from historical records alone. Over the past several decades, battlefield archaeologists have made significant discoveries at sites around the world, often altering our understanding of important conflict events (e.g., Pollard 2009a).

The case study examined here is the Battle of Waterloo (1815), where Napoleon Bonaparte was famously defeated for the final time. Several factors make this site particularly suitable for the testing of large-scale geophysical methods for battlefield archaeology. There is an ongoing larger archaeological research project that provides feedback in the form of targeted excavation. The existing corpus of historical research also provides a considerable database of ancillary data to lend context to archaeological/geophysical findings. The site is also characterized by relatively homogenous soil conditions and has been afforded long-term legislative protection which has limited anthropogenic disturbances in the time since the battle. Much of the landscape is open and relatively flat terrain, making it suitable for motorized survey configurations. Despite being relatively well protected from obvious large-scale disturbance, however, the site is threatened by other agents, primarily soil erosion related to mechanized agriculture and illicit removal of archaeological material by non-licensed detectorists. Thus, there is a tangible need for the large-scale documentation of archaeological resources and an understanding of their state of preservation.

Battlefield Archaeology and Historical Archaeology

Battlefield archaeology is now well established as a subdiscipline of conflict archaeology, which explores broader topics and themes related to conflict on a wide range of sites (Banks 2020).

Battlefields provided much of the initial impetus for and continue to make up the majority of work in conflict archaeology (Scott and McFeaters 2011). Much of the focus has been on large set-piece battles, though there is also increasing interest in small-scale asymmetrical warfare (Smith and Geier 2019). The development of battlefield archaeology, however, has lagged behind other serious advances in archaeology and a largely pessimistic view of its potential contributions was espoused by some prominent archaeologists of the 20th century (Noël Hume 1969).

The history of battlefield archaeology has, in large part, been a history of technological innovations and refinements in methodological approaches (Scott and McFeaters 2011). In addition to the familiar established body of archaeological method and theory, practitioners require particular approaches designed for the unique characteristics of battlefield sites. Methodological limitations of the time (mid-late 20th century) seem to be in large part responsible for the delayed development noted above (e.g., Foard 1995, p. 395), though other factors have also been documented. These include a belief that archaeology could not contribute to the study of battlefields beyond the insights provided by traditional historical study (see Smith 1994) and trepidation on the part of practitioners that their study of past conflict could be seen as glorifying war or aligning politically with certain undesirable viewpoints (Pollard 2012, p. 279).

The closely related discipline of historical archaeology, wherein many battlefield archaeologists work (Scott and McFeaters 2011; Banks 2020), followed a similar trajectory in the mid-20th century (particularly in North America) but emerged more readily as an accepted and rich subdiscipline. Its specific disciplinary orientation and aims were, however, highly contested and a “crisis of identity” ensued as to whether it should align more closely with history or anthropology (Walker 1970; Deagan 1982). Similar discussions have taken place within battlefield archaeology (Scott and McFeaters 2011, p. 105). Setting aside these theoretical debates, historical archaeology has been recognized for its ability to provide new perspectives on historical narratives, whether as a “handmaiden to history” in its earliest applications (Noël Hume 1964) or more recently as a “voice to the voiceless” (Orser 2010, p. 128).

In a similar manner, written accounts of battles can be assumed to be unreliable in many cases because of the chaotic nature of the events and the biases of participants; the material dimension thus provides another perspective (Scott and McFeaters 2011). While the latter broader premise was readily demonstrated at an early point in historical archaeology and ensured the cohesive study of documentary and archaeological evidence (e.g., Little 1992), the difficulty of approaching the material evidence from battlefields remained a considerable challenge to its widespread uptake (Banks 2020). Specifically, the material record of battlefields is characteristically low-density, ephemeral, tends to have minimal stratification, and is scattered across vast areas of the landscape (Pollard 2012). While many battles involved tens of thousands of participants and can be expected to have generated appreciable material signatures, their short duration means that this evidence can be difficult to detect within larger palimpsest landscapes. Traditional archaeological prospection methods (such as test pitting, visual survey, and trial excavation) are thus not typically effective (Scott et al. 1989), particularly where exact locations of events are not well known.

A significant turning point in the development of battlefield archaeology occurred with the adoption of commercially-available metal detectors, used in systematic surveys for the recovery of conflict-related objects. This was most effectively demonstrated in the United States in the 1980s (Scott et al. 1989) but had seen sporadic use in the decades prior (Scott et al. 2012). Noël Hume (1969, p. 188) had in fact earlier predicted the utility of metal detection for artefact recovery, despite being largely dismissive of the overall contributions of archaeological research on battlefields. Hundreds of investigations have since demonstrated the valuable insights provided by a detailed study of spatial distributions of metal objects from battlefields. The use of metal detectors in a systematic fashion allows for the efficient prospection of large areas in a manner not possible with traditional prospection methods. Direct comparisons between metal detecting and other methods (primarily test pitting and visual survey) have thoroughly demonstrated the superiority of the former method for the recovery of artefacts from conflict sites (e.g., Reeves 2011; Scott et al. 2012; Balicki 2016).

The uptake of metal detectors in archaeology was initially slow, in large part due to a hesitancy on the part of professional archaeologists to adopt a tool commonly associated with illicit use (Gregory and Rogerson 1984; Connor and Scott 1998, p. 76). This negative association has since waned, with battlefield archaeology providing the catalyst for the widespread adoption of metal detecting into rigorous archaeological research. In many cases, this has also led to increased collaboration with avocational metal detectors and educational opportunities (Farley et al. 2021).

Systematic metal detector survey is now the *de facto* approach in battlefield archaeology. Its utility is most obvious in sites of the post-medieval period, which are characterized by large assemblages of metal objects, and has perhaps led to a bias towards the study of sites from this period. Increasingly, metal detection is also proving fruitful for earlier conflict sites, such as those from the Roman period (Ball 2016; Uribe et al. 2021). As with any methodological approach, however, the associated limitations must be considered. Careful thought must be given to the impact of instrument type/configuration, survey design, operator experience, target, and environmental characteristics on the outcomes of a survey. With the growing maturity of the discipline and the now-widespread acceptance of metal detecting as a legitimate and useful approach, such factors are being increasingly considered (Scott 2010; Espenshade 2012).

Compared to metal detection, the use of other geophysical methods in battlefield archaeology (for a broader range of potential targets) has been relatively limited. Given the central role of the metal detector, it is perhaps surprising that other geophysical methods have not seen extensive use. This may be partly due to the challenges, only recently alleviated (Trinks 2015), in covering large areas with many geophysical methods. Despite the relative lack of large-scale applications, a range of examples, often aimed at particular areas or targets based on documentary references, have shown the utility of various geophysical methods at different battlefield sites (Pollard and Banks 2007; Henry et al. 2017; Stele et al. 2021; Holas 2022). There is thus untapped potential for increasing the scale of these applications and further assessing the capabilities of other geophysical methods in battlefield archaeology, which ought to be highly complementary to conventional metal detection survey.

Background to Waterloo and the Waterloo Uncovered Project

Given the delayed development of battlefield archaeology, some of the world's most famous and closely scrutinized battles (in terms of historical research and public interest) have only recently received archaeological attention. The Battle of Waterloo is an example of this; despite being recognized as one of European history's most significant conflicts and having been the subject of hundreds of publications, archaeological research at the site had been very limited until its bicentenary in 2015.

The Battle of Waterloo was fought on the 18th of June 1815 between Napoleon Bonaparte's French army and a pan-European coalition led by the British Duke of Wellington and Prussian Marshall von Blücher. These armies were part of the Seventh Coalition, an assortment of European powers, formed to resist Napoleon's renewed incursions in 1815. At Waterloo, Napoleon was famously defeated, ending a campaign referred to as the Hundred Days, stretching from his escape from exile on the island of Elba in mid-March to his abdication in Paris at the end of June (Muir 2013). This brought a decisive end to the Napoleonic period in Europe and marked the beginning of a period of relative peace and political stability.

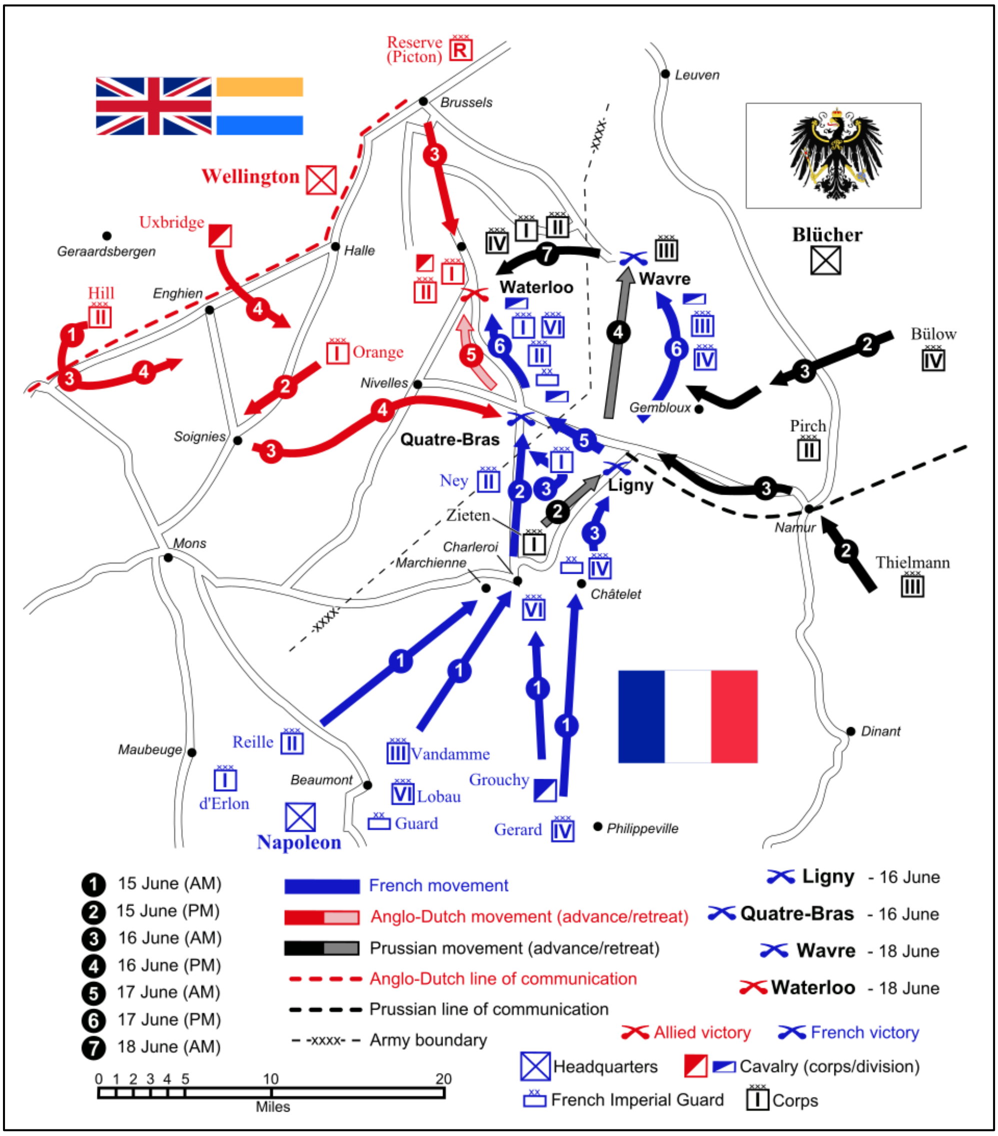

Figure 1: Map of the Belgian campaign of 1815, showing major battles and movements leading up to the Battle of Waterloo.(Wikimedia Commons, created by Ipankonin, CC BY-SA 3.0)

The Battle of Waterloo was fought on the outskirts of several villages some 15 km to the south of Brussels near the border that separates the modern regions of Wallonia and Flanders, the respectively French and Dutch-speaking areas of Belgium. It owes its name to one of these nearby villages; though it was not in fact the closest one to the battlefield, it is the location from which Wellington sent his dispatch following the battle (Adkin 2001). Napoleon's strategy in the Belgian campaign was to separate Wellington's Anglo-Allied (composed of British, German, and Dutch troops) and Blücher's Prussian armies, rather than face the combined forces with their numerical superiority. To this end, separate battles were fought on the 16th of June at Quatre Bras (French strategic victory over the Anglo-Allies) and Ligny (French victory over the Prussians). Both Wellington and Blücher then retreated north, eventually regrouping at Waterloo for the decisive battle (Figure 1).

Although the location of Waterloo seems unassuming, it possesses great strategic value on account of its situation along one of the main roads leading north to Brussels. Wellington's retreat from Quatre Bras and stand at Waterloo was coordinated with the Prussian army retreating from Ligny under Blücher, who agreed to meet Wellington at Waterloo. In addition to the strategic location, a low ridge provided a natural defensive feature guarding an extensive area of dead ground (the reverse slope). Furthermore, a series of enclosed defensible farmhouses (Hougoumont on the right, La Haye Sainte in the middle, and at Papelotte on the left) were positioned at strategic locations along and in front of the ridge and functioned as bastions to divert French attacks (Muir 2013) (Figure 2).

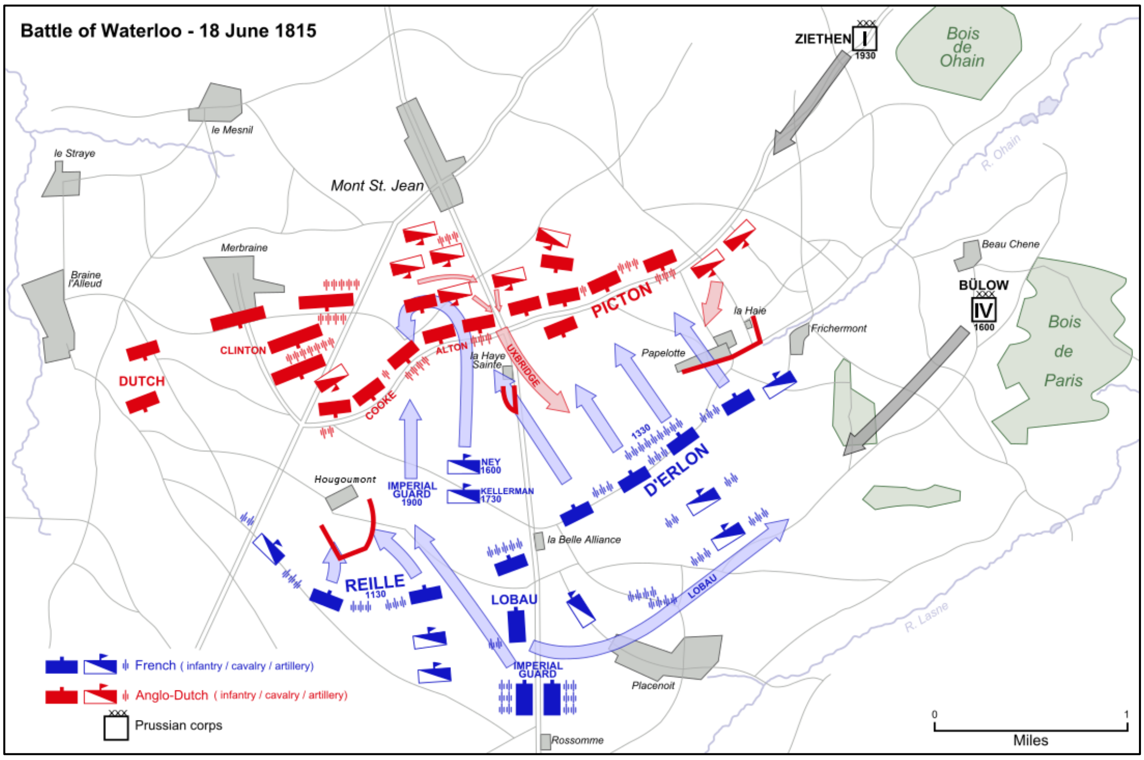

Figure 2: Simplified overview of the Battle of Waterloo. (Wikimedia Commons, public domain)

Wellington's army (numbering approximately 70,000) was deployed along the Mont St-Jean ridge and reverse slope (a front of approximately 2 km) with Napoleon's army (approximately equal in size) positioned on an opposing ridge some 1,500 m to the south (Adkin 2001). The battle began late in the morning and continued through to the late evening. Successive cavalry and infantry assaults were launched throughout the day by both sides with heavy casualties incurred. The struggle over the farm of Hougoumont, one of the first attacks launched by the French, was particularly intense and lasted for most of the day. The key turning point in the overall battle occurred with the arrival of the Prussians from the east in the late afternoon (eventually numbering approximately 50,000). Fierce fighting ensued in the village of Plancenoit, on Napoleon's right flank, and the combined Prussian and Anglo-Allied armies routed the French, forcing Napoleon to withdraw to Paris.

Today the battlefield is preserved in much the same state that it would have been in 1815 (Figure 3). A large portion (over 500 ha) corresponding to the area of French and Anglo-Allied combat was afforded legislative protection in 1914 (the first such site in Belgium to be so designated) (Division du Patrimoine de la Région wallone de Belgique 2008). Another 460 ha was added in 2015 (corresponding to the area of French and Prussian combat), bringing the total to just under 1000 ha. Aside from a small amount of urban encroachment around the village of Plancenoit, the main landuse continues to be large-scale agriculture.

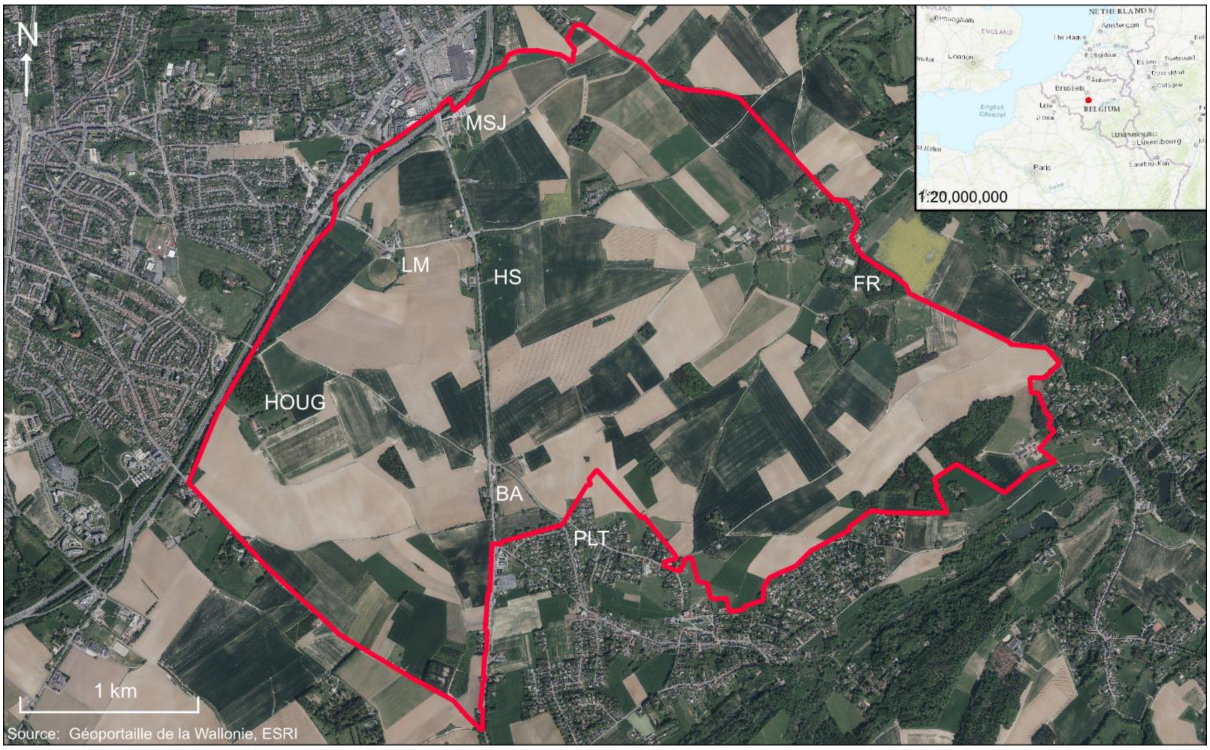

Figure 3: Recent air photo (2022) showing current conditions of battlefield of Waterloo with protected boundary shown in red. Landmarks of note annotated (see Figure 2): Hougoumont (HOUG), Mont-Saint-Jean (MSJ), Belle Alliance (BA), Haye Sainte (HS), Frichermont (FR), Lion Mound (LM). Figure by author.

The British-led charitable project Waterloo Uncovered was launched in 2015 with the aim of exploring the archaeology of the battlefield. In collaboration with archaeologists from Belgium's Agence Wallonne du Patrimoine (AWaP), archaeological work has been ongoing since then at various locations on the battlefield. Alongside and as part of its professional archaeological research, the organization aims to support serving military personnel and veterans in well-being and recovery through their direct involvement in all activities (Evans et al. 2019). Early work focused on the complex of Hougoumont and has provided important insights into the French assaults on the farm and details on its architectural layout (Eve and Pollard 2020). More recent work has examined other areas of the battlefield, including remains of a field hospital near the farm of Mont-Saint-Jean (Moulaert, Bosquet, et al. 2020; Bosquet et al. 2023). As part of the earliest work at Hougoumont, geophysical surveys were undertaken (De

Smedt 2017). Promising initial results prompted an expansion of the initiative through the present doctoral project, resulting in a collaboration between Waterloo Uncovered, Bournemouth University, and Ghent University.

Aim and Objectives

The overall aim of this research is to explore the use of large-scale geophysical prospection methods for the study of pre-modern battlefield sites, with the battlefield of Waterloo serving as a case study. Primarily using the complementary methods of fluxgate magnetometry (FM) and frequency-domain electromagnetic induction (FDEM) survey, it seeks to examine if and how geophysical methods can be effectively integrated into the larger field of battlefield archaeology. To this end, the following research questions and associated objectives are pursued:

1. **What is the potential of near-surface geophysical prospection for early modern battlefield archaeology?**
    (a) Identify archaeological targets of interest (artefacts and features) that would be expected at early modern battlefield sites.
    (b) Consider dominant methodological approaches in battlefield archaeology and how geophysical survey might be integrated into the larger workflow.
    (c) Conceptualize these targets in terms of geophysical properties and what contrasts they might render.
    (d) Identify geophysical methods best suited for survey on battlefield sites, considering instrument configurations and background environmental properties.
    (e) Consider limitations of geophysical survey for battlefield sites.

This question establishes the methodological context for the research. As noted above, the issue of methodology has been at the centre of the development of the discipline of battlefield archaeology. The material record associated with battlefield sites poses significant challenges for most forms of archaeological prospection. One issue seems to be that targets of interest are not always explicitly defined, either in archaeological or geophysical terms. The latter is a broader problem in archaeology that is only more recently being explicitly addressed, thus allowing for more efficient operationalization of geophysical survey (e.g., Verhegge et al. 2021). Clear definition of targets of interest allows for the selection of the most appropriate methods (while also considering environmental/pedological context) and subsequent evaluation of these.

2. **How can large-scale geophysical survey contribute to archaeological research at the battlefield of Waterloo?**
    (a) Identify key research priorities at Waterloo and how these might be (partly) addressed through geophysical survey.
    (b) Identify geophysical methods best suited to the detection of features of interest at Waterloo, considering likely targets and soil/geological background at Waterloo.

(c) Assess effectiveness of geophysical survey in detecting targets of interest identified above.

(d) Conduct invasive sampling to determine nature of geophysical contrasts.

(e) Consider role of geophysical survey in larger integrated workflow at Waterloo.

This question puts the framework established in the first question into practice. Waterloo is an excellent case study as it is an appropriate environment for several different methods, it is relatively well preserved, it is the recent focus of rigorous archaeological study, and the loess soil setting provides a stable and low-noise background for commonly used geophysical approaches. Surveys undertaken at Waterloo for this project represent the largest geophysical dataset from an early modern battlefield (>150 ha of data). A sampling method based on targeted invasive explorations combined with *in situ* recording of relevant geophysical properties was used to allow for more robust interpretation of sensor data. The focus here is primarily on anthropogenic targets, while the question below addresses the sedimentary context as a standalone topic.

3. **What is the influence of soil erosion and deposition of colluvium on the archaeological record at Waterloo and how can we better understand its spatial extent?**

(a) Describe mechanisms of soil erosion at Waterloo.

(b) Characterize impact of soil erosion and colluvial accumulation on the archaeological record of the battle.

(c) Consider the role of non-invasive datasets (remote sensing, geophysics) and minimally-invasive sampling in the recording of lateral and vertical extent of colluvial deposits.

(d) Develop integrated workflow for mapping erosion and colluvial deposits at multiple scales.

Extensive soil erosion has occurred at Waterloo, largely a result of intensive agricultural exploitation in recent years. Thus, despite a lack of recent development and other obvious large-scale disturbances on the battlefield, the archaeological remains are still vulnerable. This is a situation that threatens archaeological sites around the world and can also complicate the identification of certain targets of interest that can become deeply buried beneath eroded deposits. There is, therefore, value in the detailed mapping of colluvium to aid in the selection of appropriate testing strategies and assist with archaeological interpretation and site management. For this, geophysical methods are combined with other minimally-invasive approaches in an integrated, multi-scalar framework.

Thesis Structure

This is an Integrated Thesis, incorporating material in a form suitable for publication. Specifically, three paper-style chapters are included as Chapters 2, 4, and 5 (Figure 4). These individual papers each address specific aims, as outlined below, but share common methodological approaches and case studies. Thus, they form part of a cohesive research topic, which is the application of near-surface geophysical prospection methods to battlefield archaeology, as demonstrated at the battlefield of Waterloo. A short preamble before each paper notes the status of the paper at the time of thesis submission and any modifications made for inclusion in the thesis (generally, removal of self-contained components of papers to avoid redundancy and inclusion of additional discussion/examples). For all papers, the present author is the lead author and was responsible for manuscript preparation.

Following this introduction, Chapter 2 consists of a literature review that provides a more generalized framework for the methodological approaches used, thus addressing Question #1. It systematically considers the various categories of evidence that can be anticipated at a battlefield site and conceptualizes these in terms of geophysical properties and associated instruments.

Chapter 3 outlines in greater detail the methodological approach used in this work. Important concepts of electromagnetic theory are presented, followed by an overview of the geophysical techniques used in this research (FDEM and FM). The relationship between measured geophysical properties and soil and object attributes of interest is then outlined. Finally, practical issues around survey design, field deployment, and data processing are discussed.

Chapter 4 follows on from the framework articulated in Chapter 2 and addresses Question #2 by evaluating geophysical data from the large-scale surveys undertaken at Waterloo, thus considering the effectiveness of the methods used in identifying targets of interest. Contributions to the larger archaeological project at Waterloo are discussed and perspectives offered on the use of geophysical survey at similar sites.

Chapter 5 focusses on the use of complementary minimally-invasive methods for the large-scale detailed mapping of colluvial deposits at Waterloo (Question #3). It discusses the archaeological relevance of this task by considering the challenges posed by ongoing soil erosion for the preservation and identification of sensitive archaeological deposits.

Finally, Chapter 6 revisits the aims as outlined in this introductory chapter and provides a critical overview of the contribution of this work to the field of battlefield archaeology, as well as other related fields including archaeological prospection, landscape archaeology, and environmental archaeology.

All data presented in this thesis are deposited at the Department of Environment, Ghent University, Belgium and available upon reasonable request.

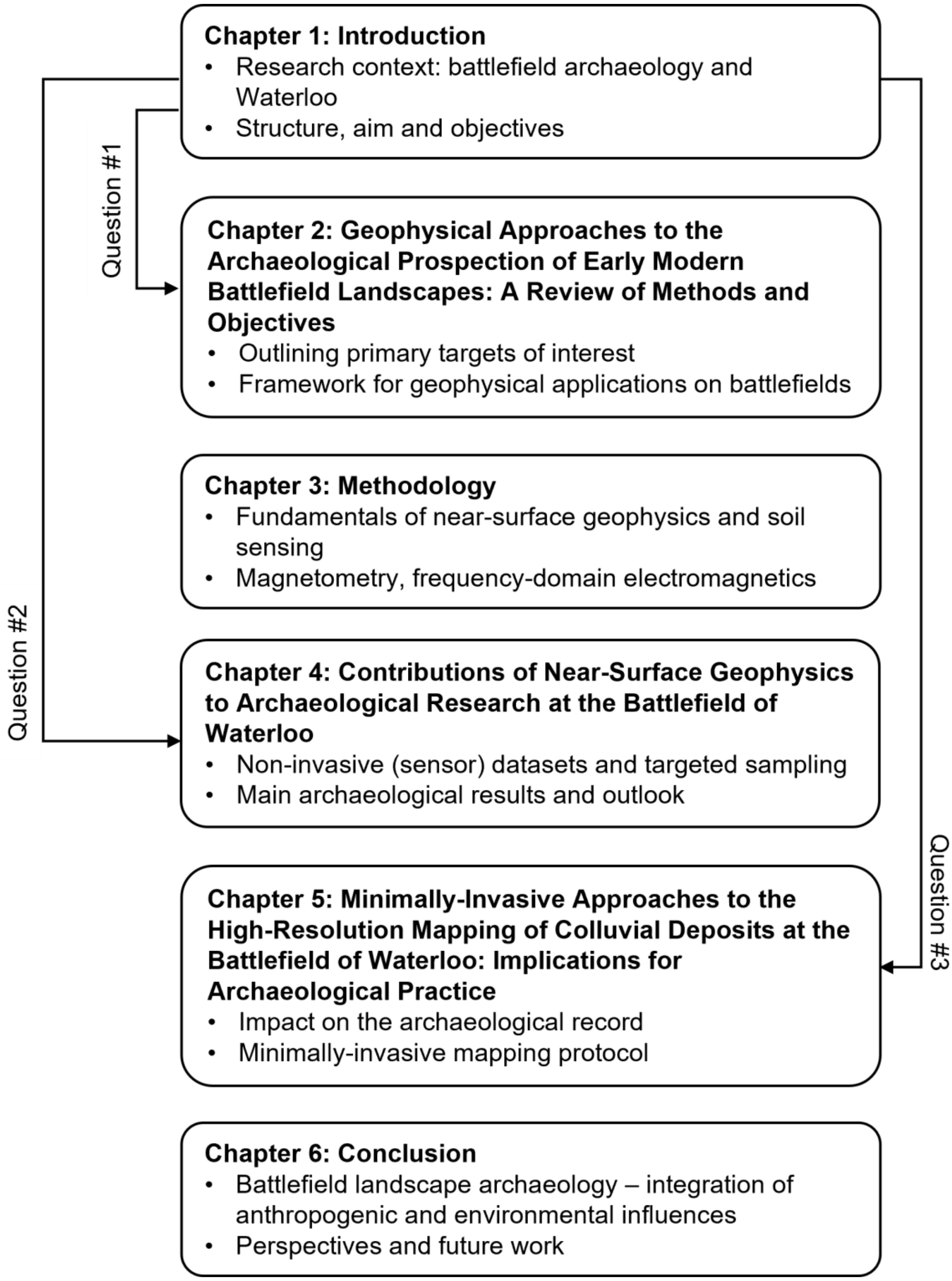

Figure 4: Structure of thesis. Figure by author.

Chapter 2: Geophysical Approaches to the Archaeological Prospection of Early Modern Battlefield Landscapes: A Review of Methods and Objectives

This chapter is based on a paper published in *Journal of Conflict Archaeology*: Minor modifications include updated references.
Williams, D., Welham, K., Eve, S. and De Smedt, P., 2024. Geophysical Approaches to the Archaeological Prospection of Early Modern Battlefield Landscapes: A Review of Methods and Objectives. *Journal of Conflict Archaeology*, 19 (1), 6–41. https://doi.org/10.1080/15740773.2024.2330916

Introduction

Battlefield archaeology aims to further our understanding of short-term episodes of conflict through the study of material remains and elements of the historic landscape. Objectives typically include the spatial delineation of areas of combat and ancillary activities, as well as the enhancement of historical accounts through an analysis of physical evidence. As a relatively new discipline, having gained increased recognition over the past several decades (Banks 2020), methodological approaches are continuing to be refined. The theoretical and historical development of the field has been adequately covered elsewhere and will not be repeated here (Freeman 2001; Foard et al. 2003; Pollard and Banks 2005; Scott and McFeaters 2011; Homann 2013; Banks 2020). This chapter is concerned with methodological approaches in battlefield archaeology and specifically with how a range of geophysical methods might be more effectively integrated, taking advantage of recent developments that have enabled increasingly large, high-resolution datasets.

The comments of Ivor Noël Hume, one of the foremost figures in the early development of Anglo-American historical archaeology, appear to summarize the feelings of many archaeologists towards the study of battlefields for much of the 20th century: "*Little can usefully be said about battlefield sites… the salvage of relics becomes the be all and end all*" (Noël Hume 1969, p. 188). He felt that battlefield sites lacked archaeological integrity and were devoid of meaningful stratigraphy, suggesting that careful recovery and recording of any related artefacts would have little to contribute (Noël Hume 1969, p. 190). Although Noël Hume was not outright dismissing the archaeological study of battlefields, he was evidently pessimistic about the potential contributions of the study of their material remains (at least insofar as the methods of the time were concerned). Aside from the methodological challenges, cultural and political motivations surrounding avoidance of perceived 'militarism' may be partially responsible for the delayed uptake of conflict archaeology (Pollard 2012, p. 729). In essence, battlefields pose a methodological challenge and have perhaps suffered in the past from a skepticism and underappreciation of their (archaeological) research potential.

Following a familiar archaeological model, material evidence from battlefields can be conceptually divided into movable (artefacts) and immovable forms (features) (Renfrew and Bahn 2018). Battlefields are, however, characterized by different formation processes than those acting on most other archaeological sites. Owing to the short duration of events, artefacts are typically deposited in unstratified or minimally stratified contexts and features are usually ephemeral, if present at all. The same is true of other non-battlefield conflict-related sites such as encampments which, despite their domestic component, tend to have an ephemeral archaeological signature resulting from short-term occupations (Smith 1994; Corle and Balicki 2006; Balicki 2011). It is worth noting that these formation processes are not wholly unique in archaeology, as a diverse range of other site types and behaviours are similarly characterized by very-short term occupations consisting of artefact scatters and often minimal stratification (e.g., Verhegge et al. 2021; Corradini et al. 2022; Fitton et al. 2022). Archaeologists working on these types of sites are faced with similar challenges in terms of attempting to unravel ephemeral events within larger palimpsest landscapes. The primary difference between battlefields and most other short-term sites is the often-enormous spatial scale of the former, which presents additional challenges for prospection.

From the above, it follows that traditional invasive archaeological field techniques are typically not particularly efficient or effective in detecting battlefield remains, a fact which has long been recognized (Connor and Scott 1998).[1] Smith (1994, p. 12), for instance, has pointed out that even when isolated archaeological resources are located with test pit surveys at conflict sites, it can be very difficult to relate these to other disparate finds and the broader landscape without undertaking large-scale excavations. This is due to the inability of invasive sampling to provide continuous data on the subsurface (Webster and Lark 2013), instead relying on geostatistical approaches to make predictions at unsampled locations throughout the study area.

Complementing invasive fieldwork, (aerial and satellite) remote sensing and other landscape approaches (including pedestrian survey, topographic survey, terrain analysis and other spatial analyses) are equally well-established methods in battlefield archaeology. The main shortcoming of these is that they offer little to no direct information on the subsurface environment. Despite this, alongside historical sources and invasive methods, they are crucial components of an integrated approach to battlefield archaeology which has recently been espoused by practitioners as particularly critical to obtaining a well-rounded perspective on battlefield landscapes (Bellón Ruiz et al. 2017; van der Schriek 2020; Stele et al. 2021).

The downsides of the aforementioned methods can be mediated by incorporating geophysical techniques, which allow detecting subsurface archaeology based on their expression in, primarily electromagnetic, physical properties (Gaffney and Gater 2003). Despite only providing proxy insight into archaeological variations, geophysical methods offer the advantage of being rapidly deployed over large areas, where they can provide high-resolution and high-sensitivity information on subsurface features of interest (e.g., Trinks et al. 2018).

For this chapter, emphasis will be placed on gunpowder-era conflict, a period which spans roughly the 17th through the 19th century (corresponding to the early modern period (Homann 2013)) and has been the primary focus of conflict archaeology. This type of conflict is characterized by its emphasis on open engagements of massed infantry armed with muzzle-loaded weaponry, supported

[1] This has been recognized as a particular problem in cultural resource management, where certain techniques like shovel test pitting and visual pedestrian survey are usually applied in a proscribed manner (Corle and Balicki 2006, p. 56).

by artillery and cavalry (particularly true of the later part of the period, with siege warfare being a more common practice earlier). Another term that has been applied to this period is ‘pre-modern’ warfare (Foard and Partida 2018), which usefully differentiates it from the global 20th-century conflicts that followed. The latter are characterized by rapid technological advances that fundamentally changed the nature of warfare (Bellamy 2016), resulting in a somewhat different type of archaeological record. The methods and archaeological targets discussed in the chapter are, however, easily extended to other periods of conflict and some examples falling outside the gunpowder era are mentioned where appropriate. In particular, examples from 20th century conflicts are considered on several occasions, as these sites have been the main focus for geophysical work in battlefield archaeology (e.g., Saey et al. 2016; Note, Gheyle, et al. 2018; Note, Saey, et al. 2018; Stele et al. 2021, 2022; Stele, Linck, et al. 2023). These are included for illustrative purposes, and it can be expected that similar results could be obtained from earlier sites.

The aim is to examine applications of geophysical survey in battlefield archaeology and to suggest further avenues of potential. Targets of interest will be considered and how these might be (or have been) investigated via their geophysical properties. It is argued that battlefield archaeology investigations should place a greater focus on a range of landscape-oriented geophysical methods and that such methods have often been underutilized or uncritically applied to date. This is in part because it is only recently that instrumentation and data processing capabilities have been developed to conduct surveys at the required scale and resolution. It has been well established that the introduction of systematic surveys with the conventional metal detector (itself a geophysical instrument), previously seen by many archaeologists as a bane in the hands of hobbyists (Connor and Scott 1998), represented a watershed moment in battlefield archaeology, providing a methodology uniquely suited to the particular archaeological records and formation processes associated with these sites (Scott et al. 1989; Pollard 2009b). This innovation allowed for accessing archaeological evidence of battles in a manner that greatly exceeded the capabilities of traditional invasive methods. It has since become the workhorse of battlefield archaeology (Balicki and Espenshade 2010) and yielded novel insights into many poorly understood sites but provides a relatively narrow view into the broader archaeological record.

Geophysical Methods in Battlefield Archaeology

The geophysical methods that have the most potential and have seen the most use on battlefield sites mirror those used in the broader discipline of archaeology. These methods focus on the characterisation of electromagnetic properties in the near-surface environment: namely electrical conductivity, dielectric permittivity, and magnetic susceptibility/permeability. Instruments include magnetometry (Aspinall et al. 2008a), ground-penetrating radar (GPR) (Conyers 2013), electromagnetic induction (EMI) sensors (De Smedt 2013), and electrical resistivity (or resistance) (Schmidt 2013) survey. Metal detectors (Overton and Moreland 2015) form a specific subset of EMI instruments, which are best-known in battlefield applications in their hand-held form (Scott et al. 2012). Not accounting for this last group, particularly when integrated into mobile configurations, these methods are all capable of high-resolution rapid survey, which is particularly critical for the prospection of battlefield sites. There is a vast amount of literature on these techniques introducing near-surface geophysical methods (Everett 2013; Garré et al. 2023), as well as their archaeological application (Scollar 1990 and Gaffney and Gater 2003), to which readers are directed for further details on operating principles, instrumentation, survey approaches, and data treatment. The volumes by Milsom and Eriksen (2011) and Schmidt et al. (2015) are also practical field manuals for a wide range of techniques. Each method of interest is briefly described below and its suitability for identifying battlefield archaeological targets of interest outlined in Table 1.

*Table 1: Overview of suitability of common geophysical methods for detecting targets of interest on battlefield sites under appropriate pedological and archaeological conditions. Within each category, the individual characteristics of particular targets are varied and will be better suited to detection via different instruments/properties (further examined in the Targets section below). (Key: * * * * = Excellent, * * * = Good, * * = Mediocre, * = Poor)*

	Metal	Burials	Field Fortifications	Encampments	Key Terrain (Anthropogenic)	Environmental
Magnetometry	* * *	* *	* * * *	* * * *	* * * *	* *
GPR	* *	* * *	* * *	* *	* * *	* * *
EMI (FDEM)	* * *	* *	* * *	* * *	* * *	* * * *
Resistivity	*	* *	* * *	* *	* * *	* *
Conventional Metal Detection	* * * *	*	*	*	*	*

Magnetometry is the most widely employed method in archaeological geophysics (Aspinall et al. 2008a). It is based around the passive measurement of the intensity of the Earth's magnetic field. Local anomalies are identified by distortions in this magnetic field, some of which may relate to sources of archaeological interest. A magnetic contrast can result from either remanent (which exists permanently independent of an external field) or induced magnetization (the result of an external field, in this case the Earth's, as determined by an object's magnetic susceptibility) contributed by a buried feature. These features express themselves through a variety of different forms/pathways of magnetic enhancement and contrast (Fassbinder 2015).

GPR is an active method that uses high-frequency electromagnetic energy (radiowaves) to identify contrasts in electrical permittivity (a measure of the polarizability of a medium or how readily it slows an electromagnetic wave) (Conyers 2013). In practice, this relates primarily to the moisture content of the medium, as water is the biggest contributor to bulk permittivity. Reflections of varying amplitude (depending on the relative permittivity contrast) identify boundaries between different materials. When selecting an operating frequency, there is a trade-off between resolution and penetration depth, whereby a higher frequency (lower wavelength) has the ability to resolve smaller features but is unable to penetrate as deeply as a lower frequency. An advantage of GPR compared to other geophysical methods is the ability to discriminate the depth of anomalies based on the travel-time of the reflected wave. While an estimation of depth is also possible with the other methods outlined here (e.g., Murdie et al. 1999; Li 2003), this is complicated by the use of potential fields in these methods versus waves in GPR. In practice, depth estimation requires knowledge of the velocity of the wave in the subsurface (which is related to permittivity) (Conyers and Lucius 1996). A particular disadvantage of GPR is that the signal suffers from attenuation in conductive environments; thus particularly wet or clayey environments often do not allow for sufficient penetration (Doolittle and Butnor 2009).

EMI methods make use of electromagnetic radiation of a much lower frequency than GPR, which results in considerably different behaviour in the subsurface. Instruments operate in either the frequency (FDEM) or time (TDEM) domain, with the former being much more common in archaeology and the latter commonly employed in unexploded ordnance (UXO) detection (e.g., McNeill and Bosnar 2000). A primary magnetic field is emitted by a transmitter coil and the response (secondary field) is analysed by one or more receiver coils. In FDEM instruments, processing of the received signal by comparing the ratio of the two fields allows for the calculation of an apparent electrical conductivity (how easily an electric current can pass through a medium) and magnetic susceptibility (induced component only, in contrast to magnetometry which also considers the remanent component) for a given soil volume. Thus, the great advantage of the method is that information on both electrical and magnetic variations can be gathered simultaneously under appropriate conditions (low conductivity <100 mS/m) (McNeill 1980a; Tabbagh 1986a) and vertical variation can also be examined in a qualitative manner if the instrument is equipped with multiple receiver coils which examine separate soil volumes (De Smedt, Saey, et al. 2013).

Conventional metal detectors are a specific sub-set of EMI instruments, configured for the identification of small electrically conductive/magnetically permeable targets at shallow depths. They similarly exist in both frequency and time domain configurations, with the former by far the most commonly used by hobbyists and archaeologists alike. Discrimination of ferrous versus non-ferrous metals is typically possible with frequency-domain instruments (based on phase shifts associated with conductivity and reactance) (Overton and Moreland 2015, chap. 7). Most instruments rely on the qualitative interpretation of a visual or auditory signal and do not log data, thus requiring a considerable degree of subjectivity on the part of the operator. As with other geophysical instruments, careful consideration should be given to the impact of survey design and instrument parameters on resulting data sets (particularly given the considerable range of commercially-available instruments). These factors have received relatively little attention in the battlefield archaeology literature, beyond theoretical considerations (although see Scott 2010).

Resistivity methods include a range of configurations whereby electrical resistance (the reciprocal of conductivity) is measured through galvanic (direct) contact of probes with the ground (Schmidt 2013). This includes setups aimed at lateral surveys (common in archaeological prospection), as well as those focussed on vertical variations (pseudosection and tomography applications). A disadvantage compared to EMI is that direct contact is required with the ground[2]; thus, resistivity data can suffer if contact resistance is high (e.g., dry ground). Potential advantages, however, are that metal clutter have less of an effect on resistivity datasets, potentially allowing for isolating soil features of interest in areas where metal is a source of noise rather than an intended target (Note 2019). Resistivity remains an important tool in archaeological prospection owing to the relatively cheap cost of the

[2] There is also a family of capacitive resistivity techniques which do not require direct contact (Kuras et al. 2006), but these have not yet seen widespread use in archaeology.

required equipment and the robust corpus of knowledge associated with decades of application. In many cases, EMI is capable of generating similar results for lateral surveys (prospection) at a greatly increased rate, although mobile configurations for measuring resistivity have also been developed (Panissod et al. 1998; Dabas 2009; Loke et al. 2013). Where a detailed vertical sounding of a feature is required, however, smaller-scale resistivity surveys may be extremely useful (alongside GPR).

Other methods less commonly used in archaeology include microgravity and seismic techniques (Schmidt et al. 2015), relying on variations in the Earth’s gravitational field and responses to acoustic (sound) waves, respectively. These are usually deployed at resolutions too large for the recognition of archaeological targets, but there have been select successful case studies for some of the targets mentioned below.

Targets in Geophysical Approaches to Battlefields

As introduced earlier, the archaeology of battlefields can generally be divided into artefacts and features. This section outlines some specific targets that can be considered to be of most interest during a geophysical survey of a gunpowder-era battlefield. This list is not exhaustive, and the quantity and type of targets will differ substantially depending on the time period, area, site type, and local (taphonomic) conditions. While this underscores the importance of conducting documentary research to assist in the definition of likely archaeological signatures at a given site (e.g., Farley et al. 2021, pp. 5–6), the following overview provides a general idea of the typical range of features that make up the archaeology of battlefield sites. While other researchers have produced excellent overviews of archaeological signatures expected on a variety of early modern conflict sites (e.g., Harrington 2005; Sutherland 2005; Homann 2013; Farley et al. 2021), these have not explicitly considered geophysical discrimination potential. Such a geophysical conceptualization of archaeological targets is key to developing adaptive prospection approaches to battlefield archaeology. Here, a target is defined as a part of the archaeological record that is directly relevant to the events of a battle. This is the sought-after ‘signal’ in the geophysical data, which is in contrast to the ‘noise’ component that will also be present (Schmidt, Dabas, et al. 2020). A particular response can be conceptualized as either signal or noise, depending on the aims of a geophysical investigation (e.g., metal clutter in the topsoil). It should be noted that this section presents an idealized conceptualization of the geophysical discrimination potential of these targets. As outlined in the discussion that follows, the interpretation of geophysical datasets from battlefields and identification of the relevant signal is further complicated by other factors.

Metal Artefacts

Surviving artefacts that are directly diagnostic of battlefield events are primarily metallic. These include artillery rounds, which for the gunpowder era (and particularly the later part) were overwhelmingly ferrous (including solid shot of various sizes, smaller grape shot/cannister shot, and hollow shell fragments). Non-ferrous metallic (lead) and composite artillery projectiles were also used, particularly during the earlier part of the period (Foard 2008, p. 90) but continuing as well into the mid 18th century in some cases (e.g., with the predominance of lead grape shot for naval use at this time (Pollard 2009a)). The other major category of ammunition comprises bullets fired by small arms including pistols, rifles and muskets, which were nearly exclusively lead during the period of interest but increasingly incorporated brass percussion caps and cartridges towards the end of the 19th century. These objects form the basis of most archaeological examinations of battlefields, allowing for a spatial reconstruction of troop movements, particularly in cases where the ammunition used by different sides can be differentiated (e.g., Pollard 2009a; Eve and Pollard 2020). More detailed overviews and figures of these items can be found in McConnell (1988) for artillery projectiles and Sivilich (2016) for small shot.

Weapon components are also frequently recovered and include various items associated with small arms (lock mechanisms, escutcheons, trigger guards, etc.) or melee weapons (e.g., sword hilt fragments). Larger weapon components (e.g., bayonets, armour fragments) are more rarely recovered from battlefield sites as they were frequently scavenged shortly after (Sutherland and Schmidt 2003, p. 22; Pollard 2021, p. 79). Uniform accoutrements including buttons, buckles, and other insignia are also frequently recovered and are particularly diagnostic as they often allow identification of a particular military unit.

Compared to the response of most soils, these objects generally possess contrasting electromagnetic properties, characterized mainly by high electrical conductivity, dielectric permittivity and magnetic permeability. Assuming they are buried in soils that render only a negligible response when evaluating these properties, these artefacts are straightforward geophysical targets. Alongside their specific electromagnetic material properties, the degree to which these artefacts can be detected with geophysical methods depends on a complex integration of factors including their depth, mass, shape, and orientation as well as the sensitivity of the instrument. Non-metallic artefacts, such as gunflints or stone projectiles (though these latter objects are quite rare), are equally diagnostic of gunpowder-era military activity. As these are generally produced with geophysically inert materials, expected to render insufficient contrast, they are unlikely geophysical targets compared to their metallic counterparts.

Alongside conventional metal detection, some researchers have also made attempts to use other instruments to detect scatters of metal at battlefield sites, relying either on magnetometers (Aspinall et al. 2008a; Haxell and Triggs 2012; Wiewel and De Vore 2018) or other EMI instruments (e.g., Saey et al. 2011, 2016; de Smet et al. 2012; Pertermann and Everett 2015) (Figure 5). GPR has not seen extensive use for archaeological metal detection but has been seen intensive application in the identification and classification of UXO (including for many non-metal targets) (Yarovoy 2009). For the identification of metal specifically, GPR should also theoretically be very well-suited as metal possesses an infinite relative permittivity and thus would yield a very strong contrast. In practice, this requires dense spatial sampling and a high-frequency antenna (which in turn limits depth penetration). One interesting case study is the work undertaken by Patch et al. (2015) at the American Civil War Fort Donelson battlefield, where discrete artefact clusters were identified in GPR data and correlated with objects recovered using conventional metal detection. While these methods can be deployed more rapidly than conventional metal detection (especially in mobile configurations), and offer a larger depth of exploration, this comes at a loss of sensitivity that generally prevents detecting individual artefacts <10 cm.

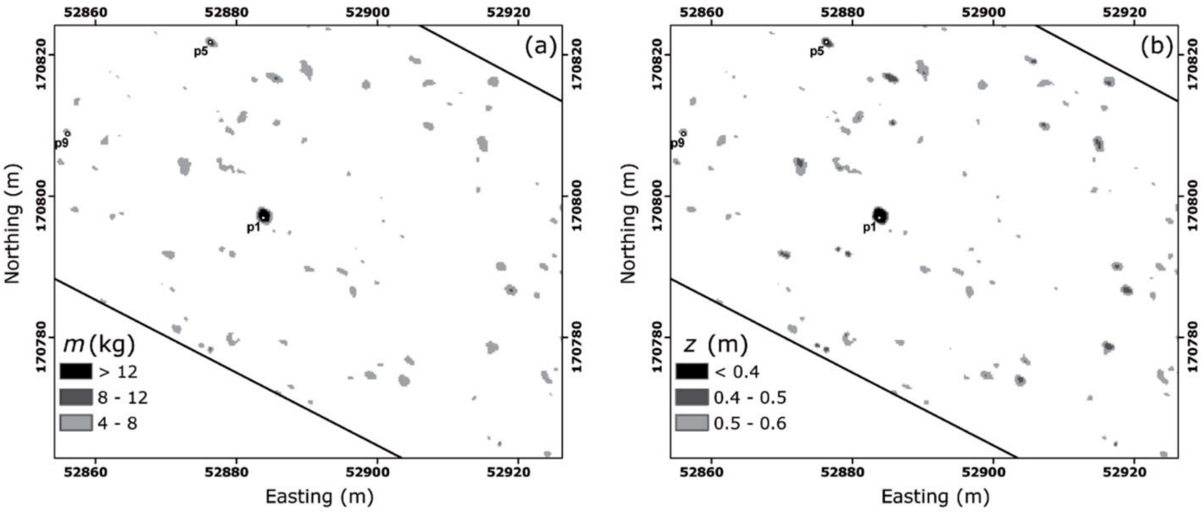

Figure 5: An example of modelled mass (left) and depth (right) of metal anomalies at a WW1 battlefield based on electrical conductivity of multiple coil pairs from an FDEM dataset. Validation of the dataset yielded ordnance or shrapnel at all (20) sampled locations where metal was predicted. Reproduced with permission (Saey et al. 2011, fig. 10).

A key distinction is the different sampling densities employed: with conventional metal detection the goal is typically close to 100% sampling density for the most intensive surveys. Only GPR in a dense array configuration (sub-decimeter sampling) approaches this and here the spatial sensitivity of the signal typically remains too low for individual artefact discrimination. Nevertheless, these methods can rapidly provide a dataset that is partly complementary to the more labour-intensive process of conventional metal detection and excavation. This might be particularly informed by UXO recovery methods (e.g., Huang and Won 2003; Yan Zhang et al. 2003). Although there is limited dialogue between the two fields, as one of the most intensively researched areas of applied geophysics there is great potential for applying insights from UXO detection (in areas such as target discrimination (O'Neill et al. 2006), evaluating soil influence (Van Dam et al. 2008), and the development of adaptive survey strategies (e.g., Achuoth Deng et al. 2020)) in battlefield archaeological frameworks. Applications of forensic geophysics have used similar methods to detect buried objects of forensic interest such as weapons (Rezos et al. 2010, 2011; Dionne et al. 2011; Hansen and Pringle 2013; Richardson and Cheetham 2013), though these objects are usually larger than most of the metal items found on battlefield sites. Controlled surveys of seeded test sites are often used to assess different techniques in forensic/UXO contexts. With limited exceptions (Heckman 2005; de Smet et al. 2012), this is an approach that has rarely been applied in battlefield archaeology.

Soil perturbations resulting from the impact of larger artillery rounds may also be detected; this effect may be similar to the type of contrast commonly observed for other types of cut/negative features and may be either electrical (related to moisture and soil texture contrasts) or, more likely, magnetic (related to the enhanced magnetism of the topsoil fill). Mapping shell holes and craters using geophysical properties has proven effective on World War 1 sites, particularly when considering both electrical and magnetic properties (De Smedt, Saey, et al. 2013; Saey et al. 2016; Note, Gheyle, et al. 2018; Note, Saey, et al. 2018). This data has also been effectively integrated with remote sensing data, including contemporary historical photographs and high-resolution LiDAR. Evidently, shelling density was much higher at 20th-century conflict sites, but these examples show the potential of these methods. Similar approaches have been suggested at earlier conflict sites (Bevan 2004, p. 19) but have not been widely reported on to date.

Burials

Casualties are an inevitable aspect of warfare and burials are thus one of the most sought-after targets, cited frequently as the most substantial archaeological features expected on battlefields (Foard and Partida 2018, p. 24). Despite this, relatively few mass graves from battlefields have been conclusively identified (Curry and Foard 2016). A considerable amount of literature (Bevan 1991; Cheetham 2005; Gaffney et al. 2015; Pringle et al. 2020; Berezowski et al. 2021) has been dedicated to the geophysical detection of both ancient and modern burials, a task which remains quite challenging. More recently, a range of remote sensing techniques have also been applied to the detection of burial sites in forensic contexts, ranging from satellite-based platforms to UAVs (Evers and Masters 2018; Murray et al. 2018; Norton 2019; Parrott et al. 2019). These techniques rely primarily on vegetation indices and may be applicable to archaeological cases, though these present additional challenges. Because vegetation effects and geophysical signatures may not be directly correlated (Cheetham 2005, p. 67), there is great value in combining these methods.

A range of geophysical techniques have been used on battlefield sites in an effort to identify locations of graves (e.g., Sutherland and Schmidt 2003; Masters and Enright 2011; Pollard 2011; Patch et al. 2015; Schürger 2015; Sherrod et al. 2020; Bonsall and Hogan 2021), sometimes in combination with other forensic methods (Bigman et al. 2023). Burial features may be revealed on the basis of electromagnetic contrasts associated with soil perturbations from their excavation and filling (e.g., Fassbinder 2016), magnetic enhancement associated with cremation (e.g., Linck et al. 2022), or the presence of associated (metal) items or other grave furniture (Půlpánová-Reszczyńska et al. 2017). Human remains themselves will rarely produce any noticeable geophysical contrast, particularly in an archaeological setting, although decomposition of the body in forensic contexts appears to be responsible for some detectable changes (Cheetham 2005, p. 68).

As with other targets, the effectiveness of geophysical methods for the detection of graves is dependent on local pedological conditions and formation processes governing the contrast between the burial and the background medium. Magnetic contrasts from the excavation of a grave itself are typically fairly minimal compared to other cut archaeological features. A subtle negative anomaly resulting from disruption/randomization of either the natural remanence or redistribution of magnetically enhanced topsoil has been noted in a variety of forensic contexts but is less likely to occur in archaeological situations due to the homogenization of topsoil over a longer period (Cheetham 2005, pp. 77–79). There are, however, some notable archaeological examples where the phenomenon of immediate backfilling of graves resulted in lasting negative anomalies (Fassbinder 2015) (Figure 6). Magnetic enhancement of a grave fill in the presence of microbial activity enabled by the decaying remains has also been theorized (Cheetham 2005, p. 78), though few examples have been reported and it can be difficult to distinguish this enhancement from other magnetic forms (Linford 2004; Juerges et al. 2010). Interestingly, it has also been suggested that mass graves with rapidly decaying tissue may lead to anaerobic conditions where magnetic enhancement of iron oxides through reduction followed by reoxidation can readily occur (Dent et al. 2004; Cheetham 2005, p. 78). In cases where cremation was undertaken prior to burial, as documented on some battlefields (e.g., Pollard 2021), there is likely a greater chance of observing an anomaly related to magnetic enhancement (e.g., Linck et al. 2022), either from thermoremanent magnetism if the Curie temperature is surpassed or through ferrimagnetic enrichment of iron oxides.

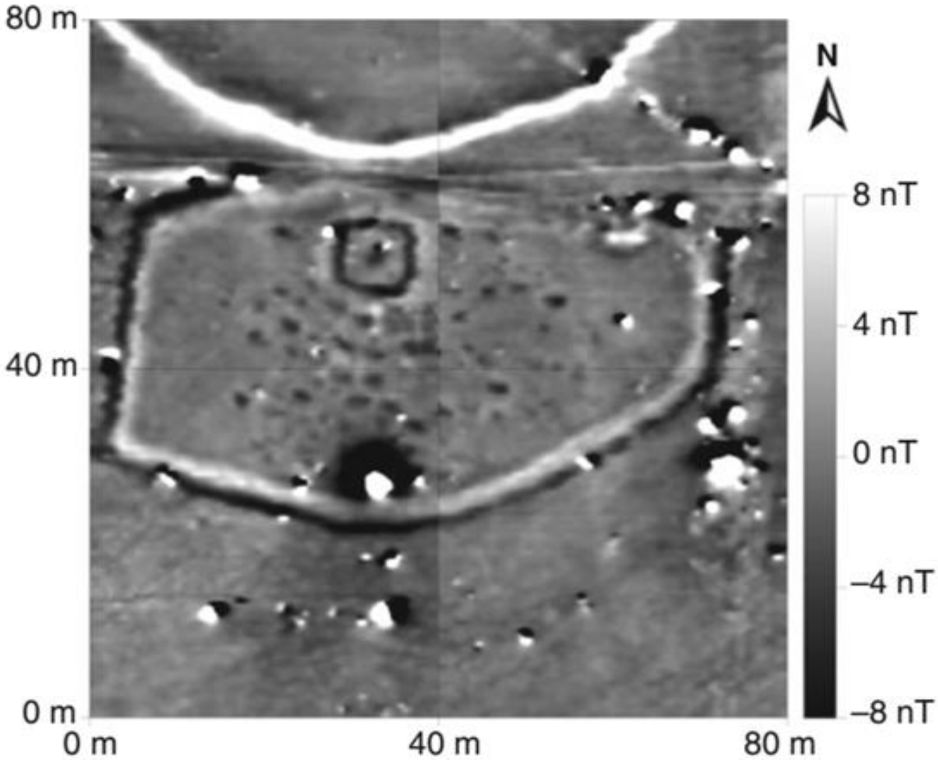

Figure 6: Example of magnetometry dataset with single grave features appearing as negative (dark) anomalies at a 17th-century cemetery in Kazakhstan. Reproduced with permission (Fassbinder 2016, fig. 6)

Electrical contrasts associated with burials have been shown to be extremely dynamic in forensic contexts, influenced by the decomposition of the body (leaching of conductive fluids) and changes in the porosity of the fill in the immediate aftermath (Cheetham 2005; Jervis 2010; Juerges et al. 2010). Such factors are of course typically absent from graves encountered in archaeological contexts.[3] Here, electrical contrasts might still be expected due to the contrasting characteristics (primarily moisture retention) of the grave fill (Gaffney et al. 2015) but, in practice, such a contrast has proved challenging to detect consistently in archaeological settings. There are reported examples of graves appearing as either conductive (e.g., Bevan 1991) or resistive (e.g., Bigman 2012) features, relative to the background medium. This variability is exacerbated by the impact of seasonal moisture variation on electrical datasets (Boddice et al. 2017; Schmidt 2017), a phenomenon which has been examined in controlled settings for forensic burials (Jervis and Pringle 2014). Nevertheless, the potential for such an electrical contrast related to a grave fill exists. Contrasts in permittivity as seen in GPR datasets, while also affected by moisture variation, have been quite effective and it is generally agreed in the

[3] An associated geochemical enrichment may still be present (Oonk et al. 2009) but this is not yet a widely used method for the detection of archaeological burials.

archaeological and forensic literature (Bevan 1991; Cheetham 2005; Berezowski et al. 2021) that this method is the most effective one for locating graves in appropriate conditions (relatively resistive soils with minimal competing sources of noise – tree roots, animal burrows, etc.) (Figure 7, Figure 8). This has also been borne out in investigations of battlefield graves (Sherrod et al. 2020). The consensus is, however, that a multi-method approach is the best strategy for strengthening interpretations and overcoming limitations of individual instruments (Gaffney et al. 2015).

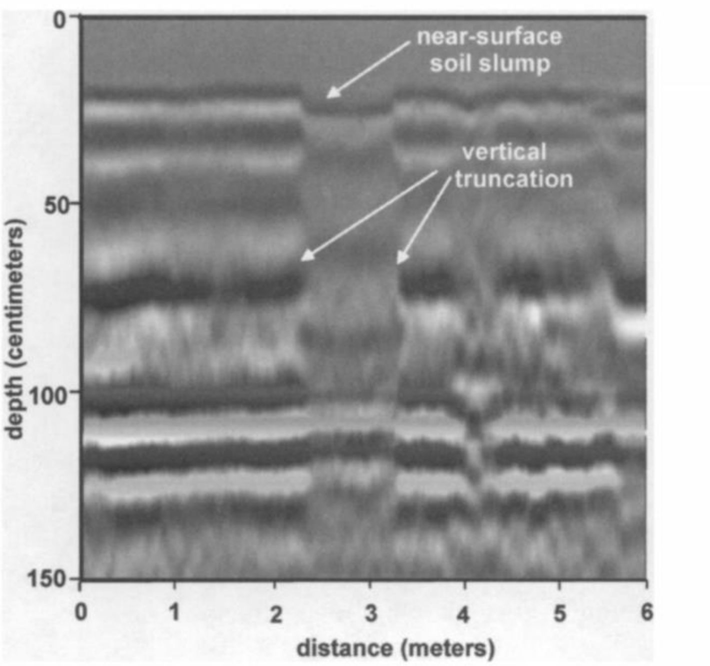

Figure 7: A likely grave shaft (without casket) seen in a GPR profile, identified by the interruption of the natural stratigraphy and low-amplitude reflections within the fill. Reproduced with permission (Conyers 2006, fig. 4)

Figure 8: GPR amplitude slice map from Fountains Abbey (UK) showing individual graves as high amplitude anomalies (darker shaded discrete variations). Reproduced with permission (Gaffney et al. 2018, fig. 2)

Graves associated with battlefields may be one of the most fruitful contexts for geophysical detection as they tend to be multiple burials ranging from a few individuals to dozens or more (Binder et al. 2014; Nicklisch et al. 2017), thus theoretically leaving a larger geophysical signature than typical non-conflict related burials. This said, single internments have also been documented on battlefields (Bosquet et al. 2015), which are much more challenging for geophysical detection. Animal burials should also be expected; these are most likely to be horses (e.g., Binder et al. 2014; Wilkin et al. 2023) associated with cavalry or horse artillery units. Burials of oxen used as draft animals have also been found in battlefield contexts (Pfeiffer and Williamson 2013). Lastly, there are several documented cases of battlefields containing deposits filled with disarticulated human remains, whether in the form of medical 'waste pits' associated with field hospitals (Pfeiffer and Williamson 2013; Pollard 2019) or secondary reinternments of comingled remains (Binder et al. 2014).

Field Fortifications

Another category of feature consists of the various expedient field fortifications which are sometimes found on battlefields (Babits 2011; Scott 2021). These might include dug features such as trenches, ditches, and pits as well as associated upstanding features, typically in the form of earthworks (e.g., ramparts, traverses, redoubts, etc.) or other more ephemeral constructions with minimal expected geophysical contrast (e.g., abatis, palisades, cheveux-de-frises). Evidently, such features will not be present at all battlefield sites and will be wholly absent from the most ephemeral skirmish-type sites. They are particularly prevalent in siege contexts (Harrington 2005) but may also be present to some degree at more short-term setpiece battles. Such hastily constructed features were occasionally used in the Napoleonic era[4], saw increased usage in the American Civil War and other mid-late 19th-century conflicts and typified the global conflicts of the early 20th century (Bellamy 2016; Scott 2021). This is largely due to strategic changes associated with the shift away from massed close-order conflict towards more dispersed skirmish-style engagements, brought about by technological developments such as the rifled musket.

More static Vauban-style fortifications have of course also seen large amounts of archaeological research (Last 2015), as well as the more ephemeral but still semi-permanent frontier forts (McBride and McBride 2011) and fortified villages and outposts (Kvamme and Wiewel 2013; Drass et al. 2019) that were particularly common in various parts of the United States. More permanent fortifications are particularly suitable to geophysical survey (Figure 9), containing large archaeological signatures similar to the substantial structural or monumental landscape features which saw much of the early focus of archaeological geophysics (Linford 2006), but these differ significantly from the more ephemeral battlefields that are the primary focus here. Rapid field fortifications have seen considerably less archaeological study (Scott 2021), which is probably partly due to the difficulty involved in identifying them with standard prospection methods and metal detection. Ultimately, constructed features at conflict sites fall along a continuum ranging from rapidly dug features for single-day conflicts (Henry et al. 2017; Holas 2022) to more substantial offensive or defensive elements of prolonged sieges (Orr and Steele 2011; Haxell and Triggs 2012; Dacko et al. 2021) to quasi-permanent fortifications (Verschoof

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[4] For instance, the Anglo-Allied force at Waterloo apparently intended to construct entrenchments to protect their artillery units on the morning of the battle as part of their defensive strategy but were ultimately unable to do so, lacking the tools and time (Muir 2000, p. 20). Flanking entrenchments were also planned at the nearby village of Braine l'Alleud but ultimately not completed (Glover 2014, p. 106).

2014), all of which have been successfully investigated using geophysics (Figure 9, Figure 10, Figure 11). In some cases, features of varying physical and temporal scales will also coexist and become intermingled as positions are modified and upgraded (Kvamme 2003). Where present, such features should theoretically be detectable by geophysical means, primarily via the magnetic and electrical properties associated with soil perturbations. In the former case, this relates particularly to magnetic enhancement associated with topsoil fills in cut features (Fassbinder 2015), while the latter contrasts pertain to moisture or soil textural variations. There is also a documented case of the use of seismic survey for the characterisation of earthwork features associated with Hadrian's Wall (Goulty et al. 1990).

Tunnels are another target for which seismic methods have been successful (Sloan et al. 2021), as well as microgravity and electrical methods (Orfanos and Apostolopoulos 2011), in addition to multi-spectral remote sensing (Melillos et al. 2018). These features are rarer on pre-20th sites but have long played a role in warfare, particularly in siege operations (Springer 2015; Olson and Speidel 2020). There are several examples of World War I and II tunnel features successfully investigated using geophysical techniques (Banks 2012, 2014; Rees-Hughes et al. 2016; Stichelbaut et al. 2017).

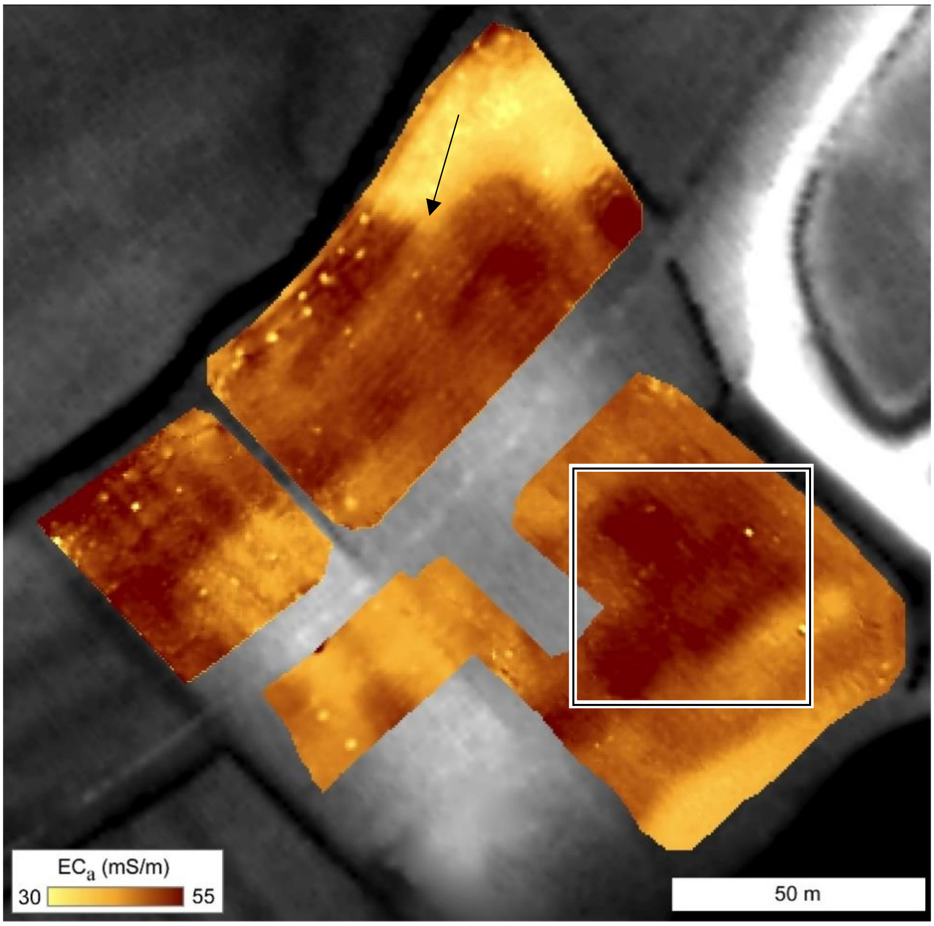

Figure 9: An apparent electrical conductivity dataset from an FDEM survey of a 17th-century Spanish fortification in Belgium, showing bastions/ramparts (high conductivity, example indicated by the bounding box) and ditches (lower conductivity, example indicated by the black arrow). Image supplied by Philippe De Smedt, 2022, used with permission.

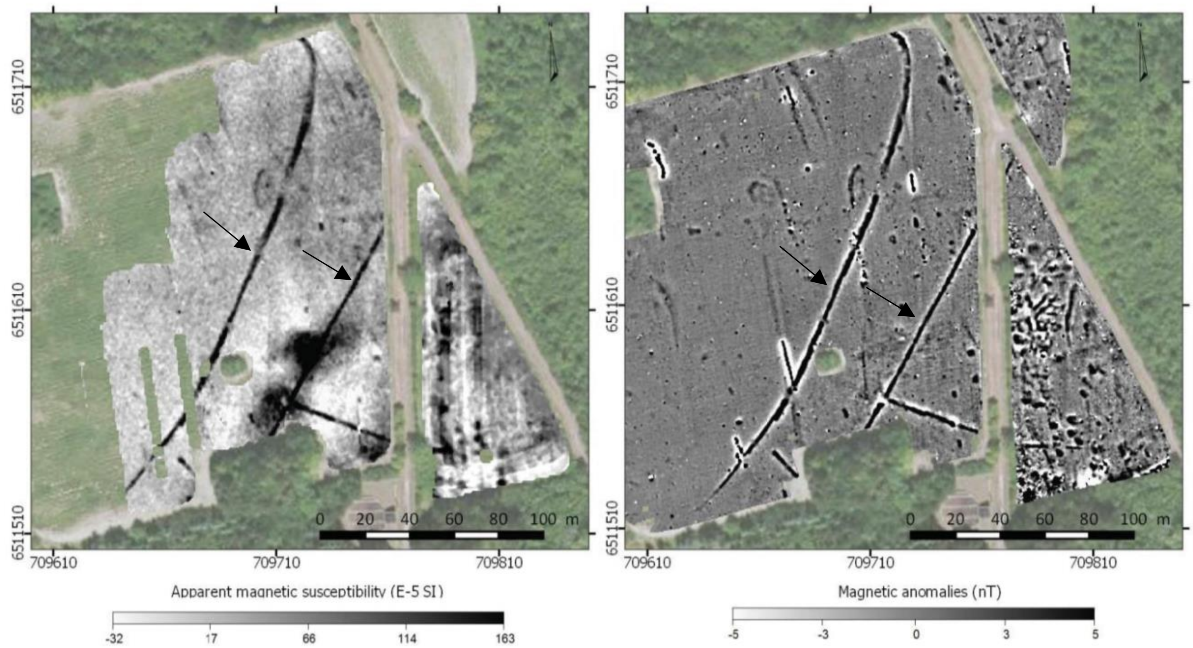

Figure 10: Magnetic susceptibility (FDEM - left) and flux density (magnetometry - right) survey data from the Roman siege of Gergovia, France showing ditch features (linear strongly magnetic anomalies indicated by arrows). Reproduced with permission (Simon et al. 2019, fig. 2)

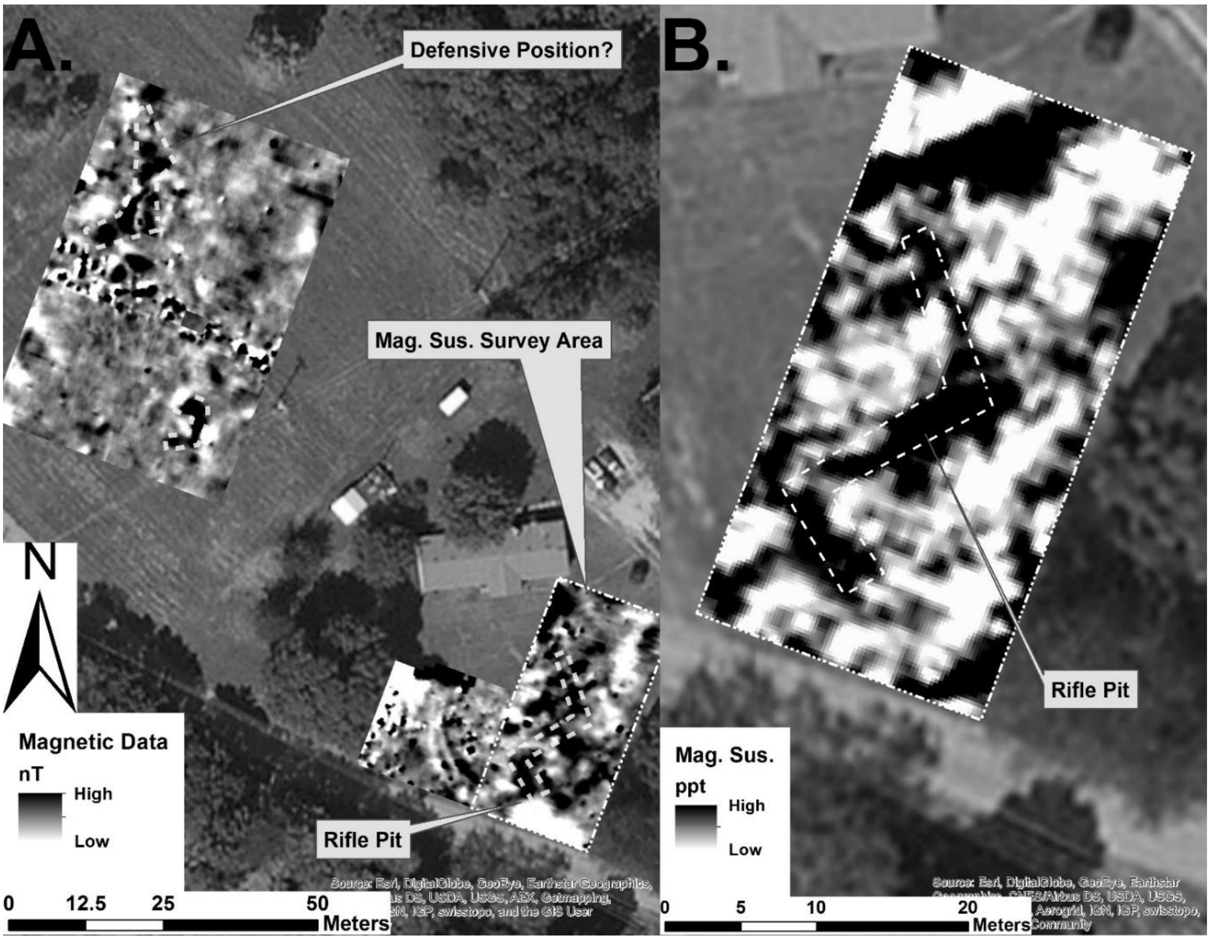

Figure 11 Magnetic anomaly in magnetometry and EMI data associated with a Civil War rifle pit at Tebbs Bend, Kentucky, USA. Reproduced with permission (Henry et al. 2017, fig. 10.3)

Encampments

Aside from strictly defensive features, other features related to the encampments of soldiers located near the site of a battle will also be present in almost any conflict scenario. The archaeological signature of these features will evidently vary significantly depending on the duration and nature of the occupation. Conflicts from later periods are likely to have larger associated domestic signatures as they generally involved more participants (Bellamy 2016, p. 61) and may also be better preserved (fewer disturbances from later land use).

Some researchers have developed useful typologies to distinguish between different types of camps according to their function (Whitehorne 2006; Balicki 2011), mostly based on contemporary military documentation. Army doctrine dictated procedures to be followed in the construction and layout of camps, which provides useful templates for archaeologically-documented examples, although variations from these models can be expected in practice. The term bivouac (or surface camp) usually applies to situations where soldiers on the march would stop with minimal shelter (typically tents) and these may be situated in the immediate vicinity of a battlefield. Longer-term camps (cantonments) might be established during periods of inactivity, such as during adverse weather or truce periods and were often composed of dug-in huts. These can be considered semi-permanent establishments, in contrast to those associated with longer-term fortifications (garrisons).

There has been concerted recent international effort (e.g., Poulain et al. 2022) to study the archaeological remains of the entire range of these sites from various periods. Longer-term encampments are best represented in the archaeological record (Geier et al. 2006; Lemaire 2020), although short-term occupations associated with more mobile armies have also been identified (Kalos 2015; Danese 2020; Drnovský et al. 2021). The typical methodology is much the same as that used in the prospection of battlefield sites (i.e., with a heavy reliance on metal detection) (Balicki 2011; Bellón Ruiz et al. 2017). A number of case studies have also demonstrated the added benefit of other geophysical and remote sensing approaches[5] at these sites, often in combination with metal detection and/or excavation (Parrington 1979; Barker 2015; Patch et al. 2015; Balicki 2016; Hadley and Richards 2016; Simon et al. 2019; van der Schriek 2020; Trinks et al. 2022). It has been recently noted that “on a methodological level, it remains difficult to detect these large-scale but low-impact military features in the small windows offered by trial trenching” (Poulain et al. 2022, p. 2) and here again it is suggested that geophysical prospection potentially has an important role to play.

Structures of some form can usually be expected and these would naturally be more robust in encampments that lasted longer or took place in a wintry climate (e.g., Bevan 2004, p. 20). Those associated with higher-ranking officers would also likely be more substantial. Commonly, structures would initially consist of tents similar to bivouacking occupations before being replaced by log buildings in longer-term occupations; however, even these might have had limited subsurface expressions (Nolan et al. 2012, pp. 286–287). Aside from structural features, other domestic features at semi-permanent encampments might include privies, refuse pits, cisterns, and wells, all of which will leave definite

[5]LiDAR has been a particularly useful approach, when sufficient above-ground traces are present (e.g., Roymans et al. 2017; Gheyle et al. 2022).

archaeological and (in most cases) geophysical signatures. Magnetic contrasts are most likely to be the source of the latter, resulting either from the enhanced susceptibility of a relatively homogenous topsoil fill or the particular characteristics of a heterogenous fill (Fassbinder 2016, p. 505). These types of sites are, however, distinct from the more ephemeral bivouac encampments directly associated with short-term battle events. Nevertheless, archaeologists have documented soil features such as pits and trenches associated with encampments in battlefield contexts (e.g., Danese 2020).

The most recognizable archaeological features resulting from these campsites will likely be the numerous campfires used for cooking, warmth, and perhaps the casting of lead bullets (Balicki 2016). At some encampments, more distinct cooking pits are also present (van der Schriek and Beex 2017, fig. 4; Drnovský et al. 2021) and have been identified with magnetic surveys (Barker 2015) (Figure 12). Whitehorne (2006, p. 29) suggests that there would usually be a campfire for every eight or ten men, situated in close proximity to company tents. Hearths are a frequent target of archaeological geophysicists (Urban et al. 2019), as they usually result in an enhanced magnetic signature from the heating of the soil, either via ferrimagnetic enrichment or thermoremanent magnetization (Gaffney and Gater 2003, pp. 37–38). They have also been identified via permittivity contrasts in GPR datasets (Cornett and Ernenwein 2020). Incidentally, other intense episodes of heat related to conflict can also lead to the creation of thermally enhanced features. For example, Stele et al. (2021) identified a thermoremanent feature from a magnetometry survey of the WW2 Vossenack Ridge battlefield that they attributed to a machine-gun position that suffered an ammunition fire. There is a high likelihood of encountering these kinds of incidental burning episodes related to conflicts, especially where incendiary forms of artillery ammunition such as carcass shells or rockets were involved.

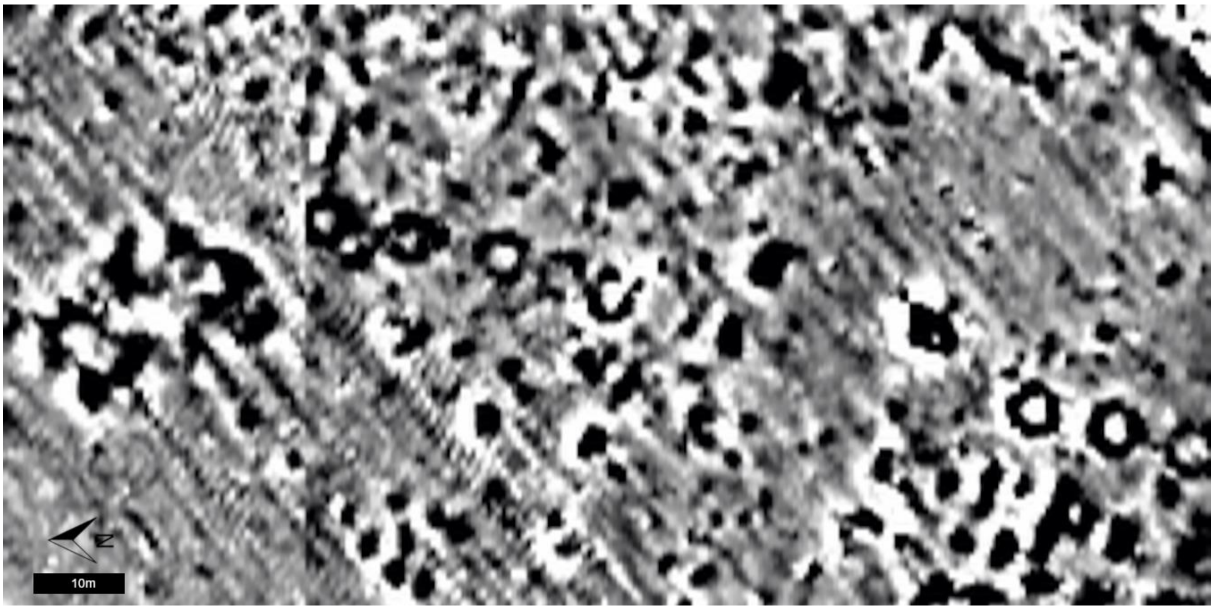

Figure 12 Magnetometry dataset from an 18th-century military encampment in Dorset. The annular features in the centre of the image are interpreted as remains of cookpits/field kitchens. Reproduced with permission (Barker 2015, fig. 9)

Key Terrain – Anthropogenic Landscape

Another broad category of evidence to be considered is anthropogenic features which were not necessarily constructed at the time of a battle but were instrumental in the course of action. An example is any existing transportation network in the landscape (paths, roads, causeways, bridges, etc.). These are particularly important as they would have served to concentrate action around them, especially in terrain that is otherwise difficult to navigate (such as boggy ground, wooded areas, tall crops, etc.). For instance, at Waterloo contemporary maps and eyewitness accounts reference a path or track in the wooded area south of Hougoumont Farm which seems to have allowed for freedom of movement for both attackers and defenders (Waterloo Uncovered 2015a, pp. 33–34). This track, along with the wood through which it passed, is no longer present in the modern landscape. Similar examples exist at other battlefield sites where roads were noted as being focal points; targeted geophysical surveys have been used with varying success to identify these features (Curry et al. 2016; Foster 2019; Lidke and Lorenz 2019). Contrast in electrical/magnetic properties can perhaps be expected based on either the road/path material itself, soil perturbations from cutting the feature, or variations in moisture retention (Gaffney and Gater 2003, pp. 142–143).

Field and parcel boundaries (e.g., ditches, hedgerows, walls) have also been noted as potentially important features in battle scenarios, as they might have been used for concealment or to limit movement (Foard 1995). These may be indicated on contemporary maps if sufficiently detailed ones exist. They have also been tentatively identified on some battlefield sites using metal findspot distributions (Bonsall 2007) and confirmed in some cases with geophysical methods such as magnetometry (Brady et al. 2007). Delineation of field systems (usually patterns of ditches and banks) using geophysical methods is a very common application on archaeological sites from a wide variety of time periods (particularly prehistoric (e,g,. Roberts et al. 2017)) and is usually undertaken on the basis of magnetic methods (e.g., Gaffney and Gater 2003, pp. 123–124), though electrical contrasts can also be expected and in some cases may even be stronger than magnetic ones (e.g., De Smedt, Van Meirvenne, et al. 2013) (Figure 13).

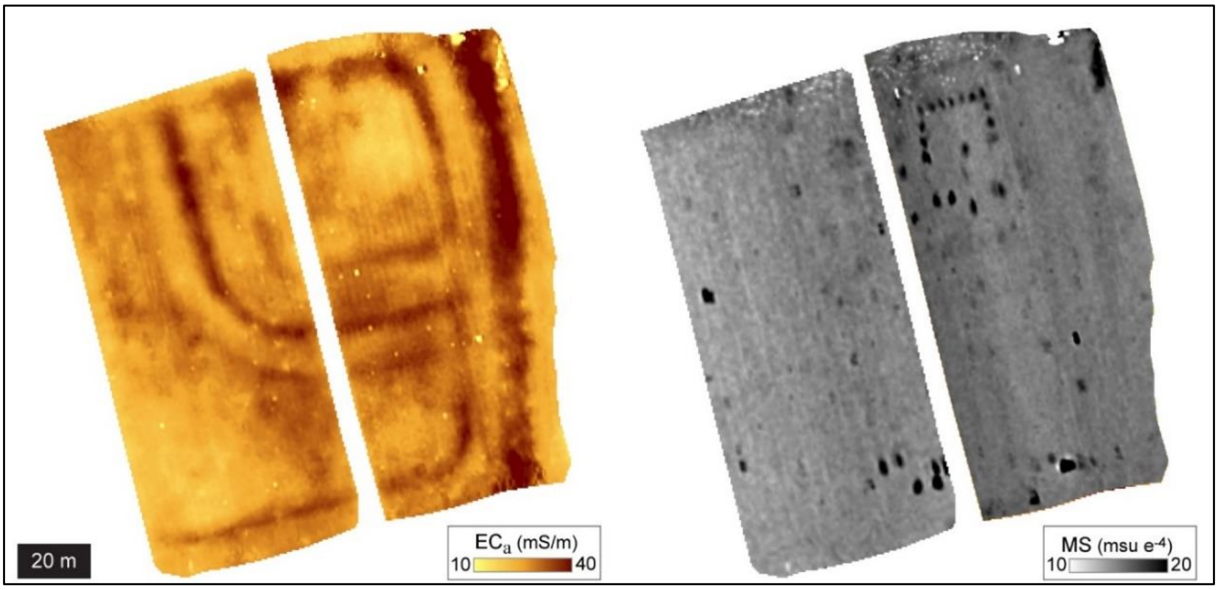

Figure 13: FDEM dataset showing clear electrical contrasts (left) indicating enclosure ditch features at a medieval abbey in Belgium. Note also the rectilinear feature visible at top right in the magnetic susceptibility data (right), the individual anomalies of which represent brick structural foundations. (De Smedt, Van Meirvenne, et al. 2013), with permission.

Another good example is existing structural features that could play important roles as defensible features in a battle, as was famously the case at Waterloo with the garrisoned farmhouses that functioned as bastions along the Anglo-Allied line (Muir 2000, p. 19). In other cases, historical references to structures have proved useful in identifying archaeological traces of battles even if those structures were minimally involved in the battle. Geophysical methods excel at identifying such structural features (depending on the type of building material, which typically presents a strong electromagnetic contrast to the background) (Figure 13, Figure 14), which could assist in targeting excavations (Doolittle 2009; Pollard 2011, p. 108; Broadbent and Ervin 2014).

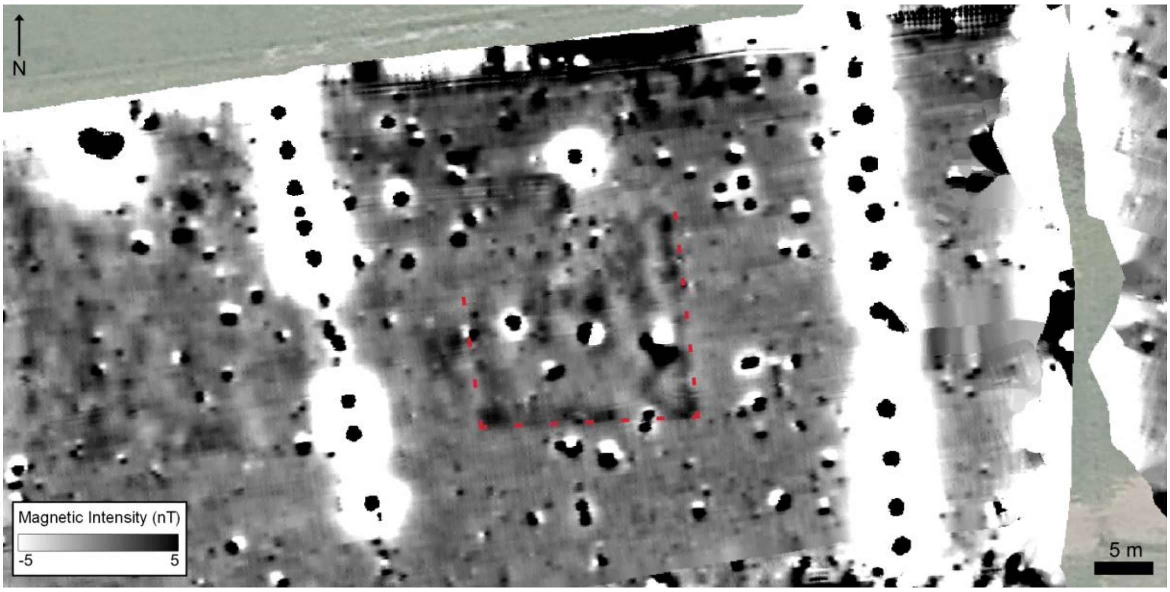

Figure 14 Magnetometry dataset from the battlefield of Waterloo showing rectilinear anomaly outlined in red, which was revealed to be the remains of a 19th-century brick structure upon excavation. Figure by author.

These types of features are instrumental to the type of terrain analysis known as KOCOA (an acronym for Key terrain, Observation, Cover, Obstacles, and Avenues) that has become an effective model for analysing the flow of military encounters (McNutt 2014; Brown 2021). In brief, KOCOA is essentially a form of viewshed and cost-surface analysis that examines physical features in the landscape in terms of their ability to restrict visibly and movement, thereby providing a tactical advantage. It has its origins in American military theory and has been particularly influential in the study of American battlefield sites (Sivilich and Sivilich 2015).

Evidently, changes in landscape over time have erased many of these defining features. Historic maps and documentary accounts should be the first resource used for reconstructing battlefield landscapes (e.g., Maio et al. 2013) but these models should also be verified using field investigations (see Holas 2022 for a comprehensive example which also incorporates geophysical survey). Where surface evidence allows it, LiDAR has been used to great effect in identifying features of interest in conflict landscapes, particularly those of the 20th century (e.g., Juhász and Neuberger 2015; van der Schriek and Beex 2017; Storch et al. 2021) where likelihood of preservation is higher but equally in earlier examples as well (Millard et al. 2009). In landscapes that do not have clear above-ground remains, geophysical surveys are the best way to rapidly assess the subsurface environment. In addition to identifying features which were present at the time of a conflict, they may allow for the identification of subsequent modifications to the landscape which have affected archaeological integrity, thereby informing on formation processes (in consultation with historic land use data) and narrowing areas for further investigation. As battlefield sites are often situated in palimpsest landscapes with considerable time depth, it can be difficult to separate features of interest from the broader landscape and understand the relationships of different components based on coarse sampling (e.g., Smith 1994, p. 12). Geophysics represent a possible avenue for delineating these different phases of land use when informed and validated by targeted sampling (e.g., excavation).

Environmental

A final category consists of what might broadly be termed environmental evidence that could prove useful to understanding landscapes, as well as site formation processes and appropriate methodological approaches. Natural landscape features such as elevated areas, hydrological systems, and valleys can function in similar ways to the anthropogenic features discussed above in terms of their impact on movement/visibility and should be considered as part of this kind of terrain analysis. Again, historic maps and other documentary features should be the starting point for identifying these kinds of features. Topographic survey and other forms of terrain analysis can be used to verify the presence of prominent features in the landscape. In the case of more recent conflicts and well-preserved landscapes with minimal later disturbances, this is likely to be an effective approach. In other cases, however, significant modifications to the landscape, whether anthropogenic or largely geomorphological, will have removed these traces. Geophysical surveys have proven to be an extremely effective way for reconstructing the paleotopography of buried landscapes in dynamic environments, even in relatively recent contexts such as those dating to the medieval period (De Smedt, Saey, et al. 2013; De Smedt, Van Meirvenne, et al. 2013; Schneidhofer et al. 2017; Corradini et al. 2022). This relies primarily on electrical contrasts which can be related to pedological variations of specific buried deposits and have been undertaken using large-scale electromagnetic methods (FDEM and GPR) (Figure 15).

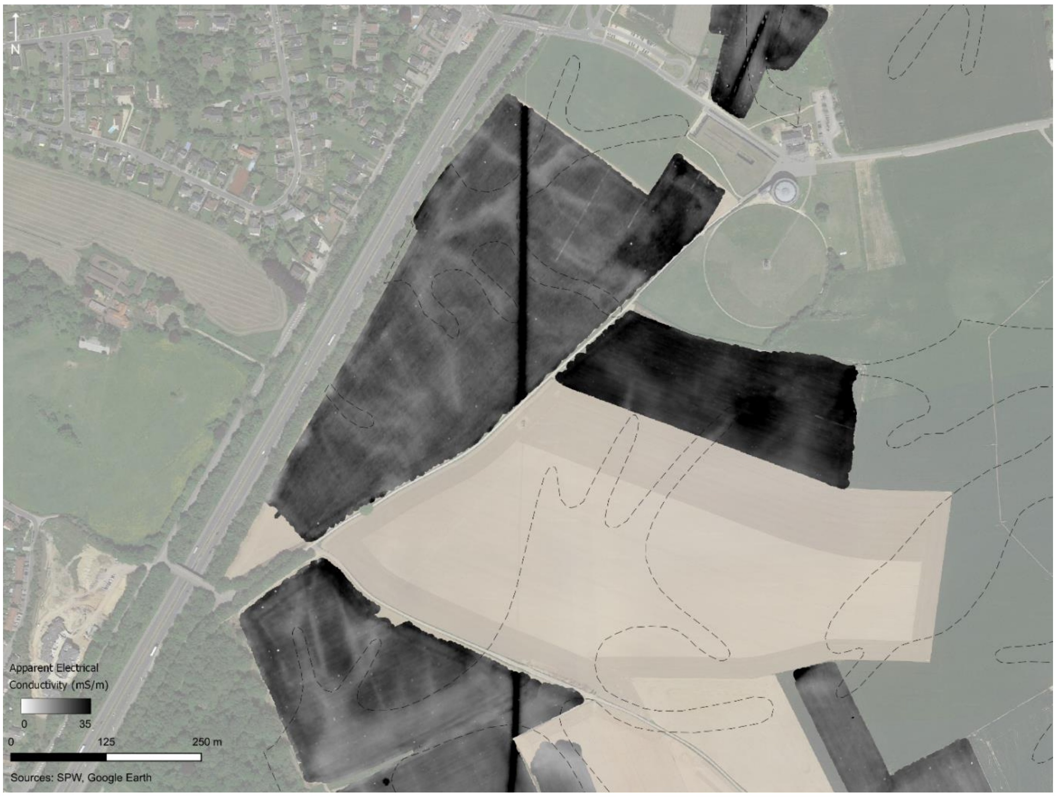

Figure 15 Apparent conductivity data from FDEM survey at the battlefield of Waterloo. Dashed lines indicate colluvial deposits (eroded soils) mapped in the mid-20th century (Louis 1958). These correlate with low-conductivity (lighter-toned) features in the FDEM dataset, which provides more detail on the distribution of these

deposits. Approaches to the mapping of colluvial deposits at Waterloo are considered more closely in Chapter 5. Figure by author.

Remote sensing techniques using multi-spectral and multi-temporal datasets have also been shown to be useful for broad reconstructions of palaeolandscapes, often relying on vegetation indices computed from infrared reflectance (Orengo and Petrie 2017). Similarly, the investigation of cropmarks in aerial photos has aided the reconstruction of battlefield landscapes such as the 1685 Battle of Sedgemoor (Foard 2003). There is great potential in integrating remote sensing and geophysical datasets across various scales of resolution. Evidently, palaeolandscape approaches will generally be more useful for earlier conflict sites which tend to be characterized by greater amounts of landscape change (e.g., Lidke and Lorenz 2019). Mapping even relatively small changes in sedimentation processes (Figure 15) is particularly relevant in battlefield archaeology, however, given the reliance on the conventional metal detector which has limitations in its depth of exploration (ca. 30 cm). While artefacts are shallowly buried at most battlefield sites (Sutherland 2004), there are also many cases of deeply buried horizons (such as colluvial or alluvial deposits) (Foard et al. 2010; Ball 2016, p. 273; Sutherland 2016; Bradley 2022) that have limited the effective use of conventional metal detectors. Thus, identifying zones which have been subject to greater post-conflict depositional processes will allow for the deployment of alternative methodological approaches (such as metal detecting in regular vertical spits (Schürger 2015, p. 121; Waterloo Uncovered 2015b; Bradley and Arnold 2017)) or interpretations. Particularly when combined with chronological information (Bradley 2022), this enhanced spatial understanding of sedimentary processes allows for more adaptive survey approaches to deeply buried battlefield remains. In the case of colluvial deposits, particular areas of the landscape are more susceptible to erosion based on land-use practices (i.e., ploughing and deforestation), topographic settings (steep slopes), and physical soil characteristics. More detailed mapping (beyond the resolution of most soil surveys) is possible on the basis of electrical variations, however, because these deposits tend to have particular pedological characteristics, especially related to soil texture (French 2016) (and consequently moisture retention).

Certain soil types have also shown to be quite problematic for conventional metal detectors[6], particularly those with high magnetic susceptibility (Igel et al. 2009; Farley et al. 2021). Some researchers have developed large-scale models of regional soil susceptibility (based on lab measurements of soil samples) and its effect on metal detector performance in the context of landmine/UXO detection (Preetz et al. 2009). Similarly, geophysical methods can be used to rapidly map volume magnetic susceptibility (De Smedt, Saey, et al. 2014), which may be useful for assessing and comparing metal detector capabilities in archaeological contexts. It is worth noting that some of these aspects discussed above – post-depositional (taphonomic) processes and pedological characteristics – are not explicitly archaeological targets in the manner defined at the outset. They are

[6] Geological and pedological conditions may also constrain the applicability of other geophysical methods (e.g., igneous base geologies can result in a large amount of thermo-remanent noise in magnetic surveys and conductive clayey soils can cause signal attenuation in GPR) (Gaffney and Gater 2003, p. 79). Such factors are also worth considering for their taphonomic impact on the preservation of targets of interest, which may impact the geophysical contrasts of features and their recognition in subsequent sampling exercises (South 2002, p. 159; Linford 2004; Kibblewhite et al. 2015).

perhaps better defined as noise (Schmidt, Dabas, et al. 2020), as they act to obscure and complicate the archaeological record. Nonetheless, they are important considerations for the investigation and interpretation of battlefield sites and can be, at least partly, identified via their geophysical properties.

Discussion

The material signatures of conflict sites vary tremendously but can be understood as being comprised of a selection of the targets described above, the majority of which are impossible to detect with the conventional metal detectors that are currently employed as the main prospection tool in battlefield archaeology. Evidently, not all of the targets described above will be present at a given conflict site. As a result, prospection strategies should be developed judiciously based on the anticipated archaeological targets. The unstratified scatters of artefacts which characterize all battlefield sites constitute the primary direct evidence of fleeting moments of conflict, but it should not be assumed that other forms of buried evidence do not exist or are not relevant. It is argued that the prospection of these subtle features is best approached using large-scale multi-method geophysics. This approach emphasizes the importance of larger landscape investigation and serves as a counterpoint to Noël Hume's contention that the unstratified artefacts are themselves the "be all and end all" (1969, p. 188). It is, however, worth noting that analysis of the (lateral) spatial distribution of artifacts (a kind of horizontal stratigraphy) is of particular importance in battlefield archaeology (Banks 2020), a point which was not recognized by Noël Hume.

Some researchers have emphasized the importance of situating battlefields in their landscape context (Foard and Partida 2018, p. 13), though the recovery of artefacts from the topsoil usually predominates (Sutherland 2004) which is probably partly due to the effectiveness of the conventional metal detector. In fact, some researchers have suggested that the widespread success of the conventional metal detector has indirectly resulted in a lack of focus on other geophysical methods in battlefield archaeology[7] (Ball 2016, p. 277). This may result in a lack of information on the larger landscape setting and other features of interest (even those that pre-date or post-date the specific moment of conflict). Landscape context can and has been examined to some degree via historic maps, terrain analysis such as KOCOA, as well as diverse remote sensing approaches. As previously noted, however, geophysical approaches are the best way to efficiently recover relevant subsurface information.

The conventional metal detector is part of a large suite of non-invasive methods routinely used by archaeologists today and is widely accepted as an important prospection tool. Its prevalence in battlefield archaeology demonstrates the importance of non-invasive prospection methods for these sites. Interestingly, it is often presented by practitioners as being in a category separate from the broader family of other geophysical methods (e.g., Brady et al. 2007; Lucas and Swain 2014) but should be utilized with the same rigour as well as knowledge of its limitations. The latter primarily including a shallow depth of exploration, subjective operation, detection of a limited range of properties/targets, and

[7] This does not seem to hold true for 20th-century battlefields (WW1 sites in particular), however, where greater numbers of geophysical surveys and relatively few professional metal detector surveys have been carried out.

a lack of quantitative archivable data which limits subsequent analysis and largely necessitates immediate excavation of anomalies. The other geophysical methods discussed above naturally suffer from their own shortcomings and limitations, especially related to pedological/geological constraints and sensitivity to other unwanted sources of noise (Gaffney and Gater 2003; Schmidt, Dabas, et al. 2020; Garré et al. 2023). The use of multiple geophysical methods allows for a more robust interpretation of subsurface features by providing complementary information and partly overcoming limitations of individual instruments; the advantages of such an integrated approach have been thoroughly demonstrated in archaeological applications (Gaffney et al. 2015; Simon et al. 2015).

A broader challenge in the interpretation of geophysical data is the notion of non-uniqueness (Verdonck et al. 2019), whereby a multitude of different models of subsurface features can lead to similar geophysical responses. As a result, many of the contrasts observed in a geophysical dataset from a battlefield will not relate to the conflict event and the task of unravelling what is relevant is quite complicated. Incorporating other data, in particular through an invasive sampling scheme targeting geophysical contrasts (e.g., De Smedt et al. 2022), is critical for constraining interpretive models leading to a more robust understanding of a geophysical data set. As a better understanding of the geophysical properties of battlefield archaeology targets evolves, more sophisticated interpretation schemes (ibid) can be developed which is particularly important for the increasingly large geophysical data sets being produced (Hinterleitner et al. 2015).

The main barriers preventing more widespread application of geophysics in battlefield archaeology, as with other forms of archaeology, are the costs and expertise required. Neither obstacle is insurmountable and battlefield archaeology is well situated as a discipline to promote increased use of geophysics given its existing (rather unique) reliance on non-invasive survey methods. The increased integration and appreciation of non-invasive prospection methods within the discipline of archaeology and the creation of equipment sharing schemes (e.g., Cuenca-Garcia et al. 2018; Welham et al. 2019) could potentially allow for more widespread usage.

It is worth emphasizing that the use of geophysical methods in battlefield archaeology is not novel, though it is perhaps still underused outside of conventional metal detection. The potential of geophysical surveys to identify archaeological features on battlefields has been recognized (Pollard 2012, p. 732) and targeted investigations, usually using manual survey configurations, have been undertaken. These are, however, typically limited by their small spatial extents often informed by potentially misleading documentary accounts. Large-scale muti-method geophysical surveys (and robust interpretive schemes incorporating invasive sampling) on pre-modern battlefield sites have to date been very limited. High-resolution mobile survey configurations now permit the investigation of very large areas and are extremely well suited to battlefield landscapes. The enormous potential of these kinds of approaches has been very well demonstrated on prehistoric landscapes (Darvill et al. 2013; De Smedt, Van Meirvenne, et al. 2014; Trinks et al. 2018; Gustavsen et al. 2020). This has also been recognized in battlefield archaeology with Curry and Foard (2016, p. 72) noting that the apparent lack of mass graves identified on conflict sites might be resolved "if more effective methods of geophysical survey are developed which allows rapid large scale survey at high resolution". These methods now exist but have yet to be widely deployed on battlefields. The generation of large-scale geophysical datasets, crucially combined with targeted invasive sampling, could assist in the documentation of underappreciated forms of archaeological evidence from battlefield sites and the refinement of survey approaches based on a more thorough understanding of the geophysical expressions of subtle targets.

Conclusion

This chapter has provided an overview of the use of geophysical methods in the archaeology of early-modern battlefields. An outline of potential targets and their associated geophysical properties is an essential first step in adaptive survey design. Alongside a consideration of site-specific conditions, this then allows for the selection of appropriate instrumentation. A range of case studies have been considered to demonstrate the broad potential of common geophysical methods for battlefield archaeology (particularly those aimed at the characterisation of electromagnetic soil properties). It is argued that geophysical approaches are particularly well suited to the large-scale prospection of battlefields situated in arable landscapes that tend to have minimal surface evidence of archaeology. While many past applications in battlefield archaeology have successfully deployed geophysical techniques, these have generally not been at the landscape scale now commonly seen in other archaeological examples.

It has also been emphasized that the investigation of battlefields must be approached using a suite of complementary methods and datasets. This essentially requires a landscape archaeology approach with a heavy emphasis on the integration of large-scale non-invasive techniques (Kvamme 2003; Cheetham 2008). While battlefield archaeologists have long adopted holistic approaches to the sites they study (e.g., Pollard 2011), there is now greater opportunity for data integration using non-invasive techniques combined with more traditional approaches, especially using GIS frameworks for analysing relationships between disparate datasets. In addition to contextualising geophysical data with documentary evidence and examining various forms of remote sensing data where appropriate, a sampling scheme is also essential for validating non-invasive sensor data. This will provide feedback for better interpreting geophysical data in addition to providing the valuable archaeological information that is the primary goal (De Smedt et al. 2022).

Applied geophysics continue to advance at a rapid pace. Particularly promising developments in archaeological prospection include the use of low-altitude UAV platforms for conducting surveys (Stele et al. 2022), thereby increasing rates of survey and mitigating challenges associated with land access for terrestrial surveys. Emphasis is also increasingly placed on monitoring schemes to better understand seasonal variations in target contrasts and the impact of various environmental factors on the detection of subtle archaeological features (Verhegge et al. 2021). This allows for a better understanding of the characteristics of targets of interest and limitations of particular instruments and survey designs. These perspectives can be incorporated into battlefield archaeology prospection, furthering the potential for studying and better understanding these complicated landscapes.

Chapter 3: Methodology

Introduction

This chapter introduces the core methodological approaches undertaken in this thesis. As previously outlined, the primary focus is on the use of large-scale near-surface geophysical methods, which comprise a suite of minimally-invasive techniques used to derive information on the subsurface environment. These are part of a broader family of environmental (soil) sensing methods, which also includes airborne remote sensing and geochemical methods. The term remote sensing is sometimes conflated to refer to both airborne (including satellite and sub-orbital platforms such as airplanes, helicopters and UAVs) and terrestrial (geophysical) applications, particularly in North American archaeological traditions (e.g., Johnson et al. 2006; McKinnon and Haley 2017). In this thesis, remote sensing is used exclusively to refer to the former category of applications. It should be noted, however, that the boundary between these approaches is increasingly nebulous. This can be seen in a rapidly growing trend in the application of airborne geophysical sensors particularly associated with the rise of commercially-available low-altitude UAVs (e.g., de Smet et al. 2021), often deployed only a few metres above the ground (e.g., Stele et al. 2022). The terms proximal and remote soil sensing are also used to differentiate these different approaches, but again increasingly represent a continuum of investigative methods and often use very similar sensors.

Remote sensing applications in archaeology have a long history dating back to the earliest use of (visible-light) aerial photos. Recent decades have seen an enormous expansion in the types of platforms and sensors used. A discussion of these is beyond the scope of this thesis but is thoroughly covered in recent review papers (Opitz and Herrmann 2018; Luo et al. 2019). For archaeological prospection, remote sensing relies on the presence of identifiable contrasts that relate to archaeological targets of interest. In the case of buried archaeology, this often takes the form of differential vegetation growth that can be linked to subsurface conditions. Remote sensing methods have shown great value in the prospection of diverse archaeological features, particularly as a more robust understanding of the conditions and properties that govern contrasts is developed (e.g., Kalayci et al. 2019; Magnini and Bettineschi 2019; Casana and Ferwerda 2023). While many remote sensing techniques offer important advantages in efficient coverage and high temporal resolution, they (generally speaking) can suffer from low spatial resolution and the inability to explore and resolve vertical variability. For the case study considered here (and many battlefield sites elsewhere), the ground surface is largely homogenized, with archaeological targets appearing to have minimal above-ground expression. For this reason, the focus here is on the use of geophysical prospection methods. Greater consideration is given, however, to the use of remote sensing methods (LiDAR and optical multispectral imaging) in Chapter 5, with a specific focus on sedimentary processes and pedological variability at Waterloo.

While there are a great variety of geophysical methods used, they all operate on the principle of measuring and modelling the spatial distribution of one or more physical properties of the subsurface in a non-invasive manner. These properties are then often used as proxies to derive information about the presence or distribution of a particular target of interest, which in archaeological surveys typically comprise buried features or artefacts of archaeological significance. These present as anomalies in geophysical datasets, requiring a measurable contrast between the feature of interest and the background medium. This contrast must exceed the level of noise present in the dataset, which can derive from various internal and external sources (Schmidt, Dabas, et al. 2020). The physical properties most relevant to archaeological targets are electromagnetic properties, which include dielectric permittivity, electrical conductivity, and magnetic permeability/susceptibility following Maxwell's equations of classical electromagnetism (Jackson 1999). A variety of seismic methods, measuring the behaviour of mechanical (acoustic) waves, are also very commonly used in near-surface geophysics (Everett 2013) but are rarely applied in archaeology (Schmidt et al. 2015) as they are more effective for deeper and larger targets. Similarly, gravity surveys measuring variations in subsurface density are widely used in other areas of geophysics (particularly hydrocarbon exploration) (Reynolds 2011) but have found only limited, though sometimes very effective, archaeological applications in the form of micro-gravity surveys.

Fundamentals of Electromagnetism

In order to understand the operating principles of the geophysical instruments considered herein and the physical properties they measure, it is necessary to consider some fundamental aspects of electromagnetism (Wangsness 1986; Jackson 1999). In-depth treatment of these concepts is also offered in applied texts aimed at archaeologists (Aspinall et al. 2008b; Conyers 2013; Schmidt 2013) and geophysicists more generally (Reynolds 2011; Everett 2013). The below synopsis is drawn from these standard references. Electromagnetism describes the interaction between electrically charged particles within electromagnetic (EM) fields. The formal relationships between electric and magnetic fields were outlined mathematically by Maxwell in the 19th century, building on many centuries of work in the separate domains of magnetism and electricity. It was only a half-century prior to the publication of Maxwell's treatise that the connection between these two phenomena was first demonstrated experimentally (with the work of Oersted and Ampère).

The movement of electrically charged particles (electrons or ions, the charge of which is measured with the unit Coulomb (C)) creates electric and magnetic fields. Current (I), measured with the unit Ampere (A), describes the rate of flow of (free) electric charge over time (C/s). The electric potential difference or voltage, measured in Volts (V), is responsible for driving current and the electrical field (E, measured in V/m) describes forces acting on charged particles. Resistance (R) occurs in the form of opposition to the flow of current. It is conceptualized in Ohm's law as a proportionality constant relating voltage across two points to current between the same two points in a conductor (R=V/I) and is measured with the namesake unit Ohms (Ω). Conductance is the inverse of resistance (1/R or I/V) and measures the ease with which an electric current passes through an object, measured in siemens (S). These are both relative (or extrinsic) measurements that depend on the amount of the measured material present. It is thus more common to speak of their bulk counterparts, resistivity (measured in Ωm) and conductivity (measured in S/m), which account for the length and cross-sectional area of the sample, providing a normalized (or intrinsic) measurement across different material types.

An additional electrical property is the dielectric[8] permittivity (ε), which describes the polarizability of a material. This effectively translates to the ability of a material to slow an EM field and store its energy. This property relates to the displacement of bound charges within a material (Jol 2009), which constitute electrons bonded to the nucleus (in contrast to the free charges described for current above). The electric displacement field (D), also referred to as electric induction, accounts for free and bound charges in the presence of an electric field: $D = \varepsilon E$. The free-space permittivity (ε_0) defines the relationship between D and E in a vacuum (non-polarizable), while the relative permittivity (ε_r, also called the dielectric constant) is a dimensionless material property comparing the permittivity of a material to that of free space ($\varepsilon_r = \varepsilon/\varepsilon_0$).

As first demonstrated by Oersted and Ampere, electric currents (moving charges) are also sources of magnetic fields. This occurs through magnetic induction, resulting in the creation of an induced magnetic field (B) surrounding charged particles (Wangsness 1986, chap. 14). This magnetic flux is analogous to electric flow (i.e., current) and is measured in weber (Wb). It is more common to express magnetic flux as a flux density (Wb/m^2) with the unit tesla (T), accounting for the area measured. This describes the magnetic force felt by a moving charge. The induction phenomenon also occurs at the atomic level where electron orbital movement and spin create small magnetic fields and elementary magnetic dipoles (north and south magnetic poles with a small separation). These dipoles will then tend to align with an externally applied field. Without the presence of an external field, however, these magnetic moments tend to be randomized and thus have no overall magnetization.

The B-field is influenced by other factors, in particular the contribution of separate internal magnetic fields from magnetic materials. Thus, there is a separate magnetic field parameter (H), also a vector, which refers to the magnetic field strength measured in A/m. This field is independent of the magnetic influence of the containing medium and describes only the influence of external currents (e.g., driven through a coil), whereas the B-field includes intrinsic (surface and volume) currents related to the magnetic material. In other words, the H-field measures the force felt on a dipole which is presumed to exist in a vacuum. In the practical case of a magnetometer reading (see below), the H and B field are very similar since the magnetometer is located in the air (i.e., a non-magnetic medium) (Everett 2013, p. 40).

The magnetic permeability (μ) of a containing medium determines the subsequent value of B ($B = \mu H$) and is an important material property expressing the degree to which a material supports the generation of a magnetic field within itself. In a vacuum, the B-field and H-field are equivalent and are related by the permeability constant (μ_0). The relative permeability (μ_r) denotes the ratio of the permeability of a particular material to the permeability of free space ($\mu_r = \mu/\mu_0$) and is a dimensionless material constant; thus, the relative permeability of free space is 1.

The induced magnetization (M) of a material similarly describes the effects of the H-field in terms of the induced magnetic moment[9] per volume (in A/m) obtained by a material. M and H are related by

[8] A dielectric is a material with insulating properties, i.e., that does not allow current flow.
[9] The magnetic moment is a vector which describes the strength and orientation of a magnetic dipole. It is the product of the current and the loop area ($m=IA$) with the unit Am^2.

an important property called magnetic susceptibility (κ, which is dimensionless as M and H have the same units), which describes the contribution of a material to an external magnetic field as a ratio of obtained magnetization to the applied field ($M = \kappa H$). Thus, it indicates how strongly a material is attracted by (or repels) an external field. As M is based on a volume measurement, κ is also normalized by volume (referred to as volume susceptibility) and is thus constant for a given material. Magnetic susceptibility is closely related to permeability with the latter expressing the total magnetization of a volume of material. Thus, the B-field represents the overall magnetization effect through $B = \mu_0(H + M)$. The relative permeability and volume susceptibility are related by the following: $\mu_r = 1 + \kappa$, implying that the volume susceptibility of free space is 0.

Relative permeability and magnetic susceptibility are used to characterize the magnetism of materials, which is determined at the atomic level by the pairing of electrons and their orbital arrangement. In diamagnetic materials (e.g., quartz, water), containing only paired electrons which do not contribute a magnetic moment, there is a net negative magnetization (repelling of an applied field) with $\kappa < 0$ and $\mu_r < 1$. When odd electrons are present, as in paramagnetic materials (e.g., many clay minerals), magnetic moments align with the applied field producing a (relatively weak) positive magnetization with $\kappa > 0$ and $\mu_r > 1$. In ferromagnetic materials (e.g., iron), dipoles in neighbouring orbital shells combine to produce stronger magnetic domains that align with an applied field resulting in strong magnetization ($\mu_r >> 1$ and $\kappa >> 0$). Permanent magnets fall within this class of materials, having a magnetization even in the absence of an applied field (termed remanent magnetization, as opposed to that induced by the external field). Ferromagnetic materials also have other subdivisions (ferromagnetic, ferrimagnetic, and antiferromagnetic) with particular behaviours of their associated magnetic domains and resulting susceptibility/permeability (Evans and Heller 2003).

Electric and magnetic fields transport energy (electromagnetic radiation) in the form of electromagnetic waves having oscillating electric and magnetic components at orthogonal angles to one another (Figure 16). This waveform symmetry and the time-varying relationship between its components was first elaborated by Maxwell, as noted above. The frequency of the oscillation determines the wavelength (and vice versa) of the radiation and situates it on the electromagnetic spectrum (Figure 17).

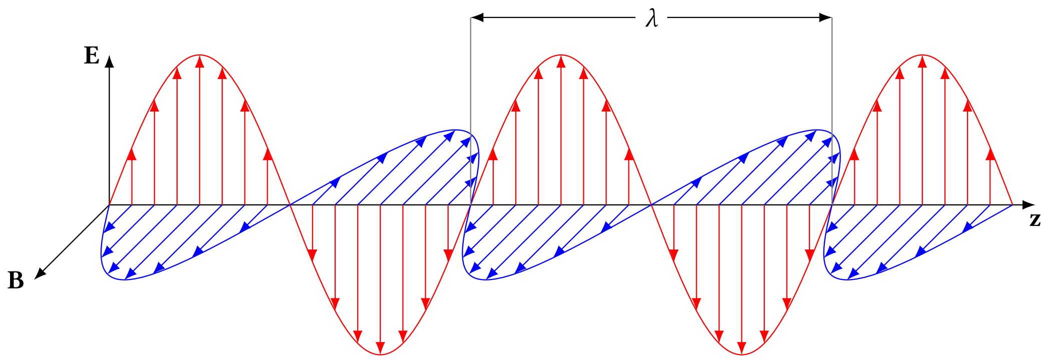

Figure 16: Electromagnetic wave model showing orthogonal electric (E) and magnetic (B) components and measure of wavelength (λ). (Wikimedia Commons, CC BY-SA 4.0)

Geophysical Soil Properties

Geophysical sensors record variations in physical properties for a given volume of soil. This section will briefly consider the main factors which govern variability in soil physical properties. Consideration of these variations as they relate to targets of archaeological interest was given in Chapter 2. Broader discussions of particular features of archaeological interest and their geophysical properties/suitability for particular methods can be found elsewhere (Gaffney and Gater 2003; David et al. 2008; Schmidt et al. 2015).

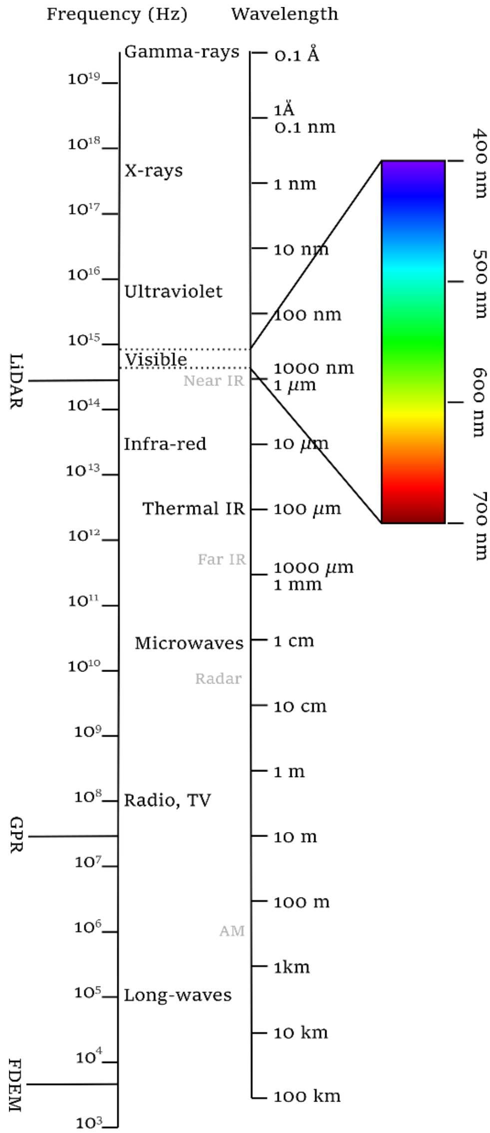

Figure 17: Electromagnetic spectrum showing position of some of the techniques discussed. (Modified by author, Wikimedia Commons, CC BY-SA 3.0)

Electrical Conductivity

Electrical conductivity in soils occurs primarily in an electrolytic form, i.e., through free ions in moisture-filled pores (McNeill 1980b). The minerals that make up the bulk of the soil matrix are generally quite resistive, so current preferentially travels through the fluid-filled pores rather than the soil matrix. It is the distribution of free charges, rather than bound charges in the case of permittivity, which determine the current pathway (Everett 2013, p. 90). Thus, in a water-saturated environment, conductivity increases with porosity (providing more space for water), as well as the amount of dissolved ions in the pore water; this is expressed in Archie's law, originally developed empirically for resistive rocks. Pore structure and connectivity also play a role. The influence of moisture content on electrical conductivity may be readily seen in surveys performed during different periods of the year, and this seasonality has a significant impact on the visibility of subsurface (archaeological) features (e.g., Schmidt et al. 2015, fig. 11).

Clay particles have different electrical properties compared to the larger sand and silt fraction, the latter being more resistive. In clay minerals, the surface typically has a net negative charge (owing to specificities of its size and mineralogical properties) that attracts and loosely binds positive ions (cations). These cations can then be exchanged with others in solution (a property measured by the cation exchange capacity), providing a pathway for current. Thus, in non-saline solutions the clay content (and indirectly the soil texture) has a significant effect on bulk conductivity. Organic matter (humic substances) can also exhibit a negative surface charge and contribute a similar effect (Blum et al. 2018, pp. 66–73).

Dielectric Permittivity

As with conductivity, the relative dielectric permittivity of water (approximately 80) is significantly higher than the mineral fraction typically found in soils (which have an approximate ε_r of 3-4). The polarization of water molecules primarily determines the velocity of radiowaves in GPR. The signal interacts with interfaces of differing ε_r, reflecting at their boundaries. Thus, the volumetric water content in a given material is the primary determinant of wave behaviour, given the stark differences between the ε_r of water and air (Everett 2013, p. 248). This is illustrated in Topp's equation. In the case of highly conductive objects (e.g., metal), which have an infinite relative dielectric permittivity, there is a complete reflection of the radiowave (no propagation).

Magnetic Susceptibility

It has been observed that there is a widespread tendency for topsoils (A-horizon) to possess a higher magnetic susceptibility than the underlying subsoil (B-horizon) and parent material, primarily due to the presence of ferrimagnetic minerals (Le Borgne 1955; Fassbinder 2015; Shirzaditabar and Heck 2022). The primary mechanism of this occurs through the conversion of weakly magnetic iron oxides (e.g., hematite) to more magnetic forms (e.g., maghemite) through the process of reduction and oxidation. This can occur in the presence of fire, either anthropogenic or natural, creating the reducing conditions necessary. The decomposition of organic material and changing aerobic conditions can also lead to this enhancement, in a process called fermentation. Finally, topsoil enhancement can occur through mechanical sorting (geomorphological) and other organic (bacterial) or inorganic pedogenic processes (Fassbinder 2015). Contrasts in the presence and distribution of magnetic minerals in a measurement volume is thus responsible for the identification of induced archaeological anomalies (which can be either more or less susceptible than the surrounding matrix).

A degree of remanent magnetism can also occur, which can be obtained through several different pathways (Fassbinder 2015). The most common of these is thermoremanent magnetism (TRM), which occurs by heating a material above its Curie temperature (e.g., 580 °C for magnetite and 680 °C for hematite (Petersen and Bleil 1982)), and subsequently cooling it. Above this material-specific temperature magnetic domains in the sample are reorientated and randomized, rendering it paramagnetic. Upon cooling, the domains realign in the direction of Earth's ambient magnetic field and acquire a permanent magnetization. This process can occur through anthropogenic activity (e.g., firing objects in a kiln) but is also an important natural process (e.g., in the formation of igneous rocks). It is important to note that (ferri)magnetic enhancement can occur even if the Curie temperature is not reached, through the conversion process described above. This has been observed in loess deposits at temperatures above approximately 400-450 C (Deng et al. 2005, fig. 3), which is well within the typical range of anthropogenic campfires (Bellomo 1993). It has been observed, however, that even very shallow soil depths (< 5 cm) are largely thermally unaffected by surface fires (Scotter 1970; Drooger 2009), though this effect appears to be more pronounced in campfires/hearths than in grass fires or stump fires (Bellomo 1993, fig. 4; Werts and Jahren 2007, fig. 2). Nevertheless, it is possible that a heated sample will be characterized by both enhanced induced magnetism as well as remanent magnetism.

Depending on the specific property of interest and depth of investigation required, a range of sensors and instrument configurations are used. An overview of the methods typically used in archaeological research was provided in Chapter 2 and additional background information on these methods in archaeology (Gaffney and Gater 2003) and in near-surface applications (Everett 2013; Garré et al. 2023) more generally can be obtained elsewhere. In the following section, the focus will be on two particular methods (fluxgate magnetometry (FM) and frequency-domain electromagnetic induction (FDEM)) which form the basis of the survey approach undertaken for this work.

Operating Principles of FDEM and FM

FDEM

There are several different instrument configurations now routinely used in archaeology which can be described as low-frequency electromagnetic methods. These methods rely on the premise of electromagnetic induction or the creation of an electric current by a changing magnetic field (Wangsness 1986, chap. 17). They operate in either the time or frequency domain, meaning that the signal is interpreted either as a function of its return/decay time or as a function of its changing frequency. The most common of these instruments is the conventional metal detector, typically configured as a frequency-domain instrument with concentric coils and referred to as induction balance (IB) or very low frequency (VLF) detectors by manufacturers (Overton and Moreland 2015). Time-domain instruments are also commonly used for metal detection (by hobbyists and professionals alike) and are typically referred to as pulse induction (PI) detectors. While frequency-domain instruments emit a continuous time-varying (sinusoidal) wave form, time-domain systems make use of a square or pulsed waveform.

Frequency-domain instruments configured for purposes other than the detection of small metal objects include the so-called Slingram family of instruments, which originated in Sweden in the 1930s (Viberg et al. 2009). These are a particular configuration whereby a transmitting coil and one or more receiving coils are fixed at relatively short distances on a rigid boom. Also commonly referred to as ground conductivity meters in the literature, their primary early application was as a means of providing a straightforward contactless measurement of subsurface electrical conductivity (as opposed to the galvanic contact required for resistivity techniques) (McNeill 1980a). The term small-loop is also used and succinctly describes the short coil separation that characterizes these instruments aimed at evaluating the shallow subsurface. Throughout this work, FDEM will be used as a shorthand to refer to this particular instrument configuration. Despite an early recognition of their potential applications (Tabbagh 1986a, 1986b), the use of FDEM instruments in archaeological prospection lagged significantly behind other instruments until quite recently.

Geophysical sensors are often described as either passive or active depending on whether they measure an ambient naturally-occurring energy source (in the former case) or emit their own signal and interpret the response. FDEM is an active technique that functions by transmitting a low-frequency[10]

[10] This low operating frequency differentiates FDEM from ground-penetrating radar (GPR) instruments which operate in the range of 10 MHz to 1.5 GHz. Because of these different frequencies, the transport of EM energy in

(~1-100 kHz) primary magnetic field from one coil and measuring the response of a soil volume (secondary magnetic field) at a second coil at a fixed distance from the transmitter. The primary field induces electric (eddy) currents in conductive parts of the subsurface, which then contribute to the secondary magnetic field measured at the receiver (Figure 18).

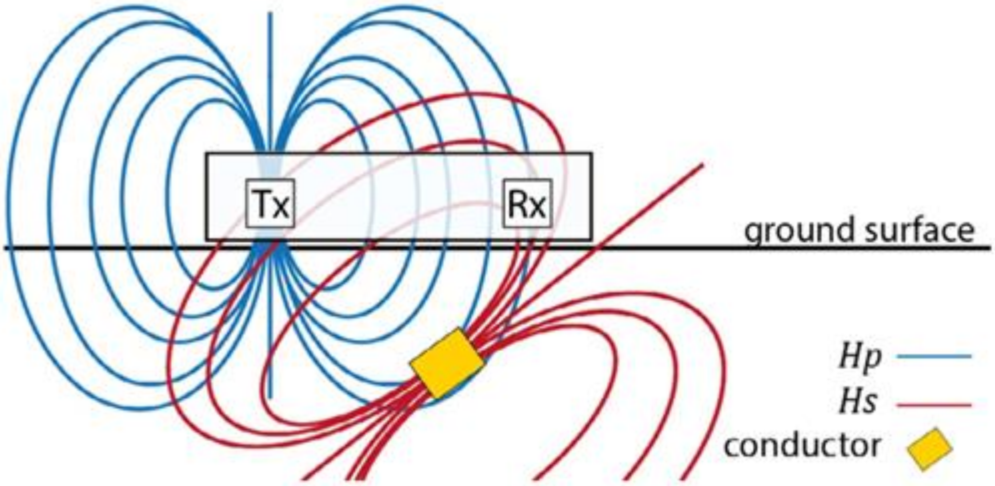

Figure 18: Working principles of FDEM, showing transmitting coil (Tx), receiving coil (Rx), primary field (Hp), and secondary field (Hs). From Garré et al. (2023, fig. 3), used with permission of copyright holder (Philippe De Smedt).

Primary processing of the received signals by comparing the amplitude and phase lag of the secondary magnetic field to the primary renders quadrature phase (QP, 90° out of phase) and in-phase (IP) signal intensities expressed in parts per million (ppm). These can then be converted to electrical conductivity and magnetic susceptibility, respectively, through inversion (e.g., Guillemoteau et al. 2016; Delefortrie et al. 2018). Simplified solutions valid within specific boundary conditions can also provide apparent values (ECa in mS/m and MSa as a dimensionless ratio) without requiring inversion. The most commonly used is the low induction number (LIN) approximation which assumes low operating frequency, small coil separation and relatively low conductivity (< 100 mS/m) (McNeill 1980a; Tabbagh 1986a; Callegary et al. 2007). In such conditions, the signal ratios measured by the instrument are quasi-proportional to EC and MS. These are considered to be 'apparent' values of these properties, as they correspond to bulk measurements over an assumed homogenous soil volume. The contribution of particular heterogenous elements of the soil matrix depends on their depth, and evaluating the true distribution of the variation of the property of interest requires fitting to a model using an inversion procedure.

If an FDEM instrument is equipped with multiple receiving coils, it is possible to measure multiple different soil volumes simultaneously to undertake a form of depth sounding (Garré et al. 2023, p. 5). This adds a vertical dimension, as larger coil separations target deeper soil volumes. The orientation of the coils also has a significant impact on the characteristics of the response, including its volume,

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the subsurface takes place in different ways. For the high frequencies of GPR, it is wave propagation that dominates, while the mechanism of transport in FDEM is diffusion. For this so-called diffusive regime, the ground conductivity influences the response with permittivity playing a minimal role (in direct contrast to GPR) (Everett 2013, p. 200).

sensitivity, noise level, and anomaly characteristics (sign and shape) (Tabbagh 1986b). Coil configurations describe the relationship between the transmitting and receiving coil(s) (Figure 19). The most commonly encountered include coplanar (where the coil axes are parallel) and perpendicular (PRP), where the receiver is oriented perpendicular to the transmitter. Coplanar configurations are typically either horizonal (HCP, also called vertical dipole) where each coil has a vertical axis (i.e., perpendicular to the ground surface) or vertical (VCP) where the coils are oriented with a horizontal axis (i.e., turned 90° from HCP). The operating frequency of the instrument also impacts the response and some instruments are configured with multiple frequencies. These are less frequently used in archaeological prospection at present but have some interesting potential applications such as the ability to diminish the influence of metal objects on the response (Simon et al. 2021).

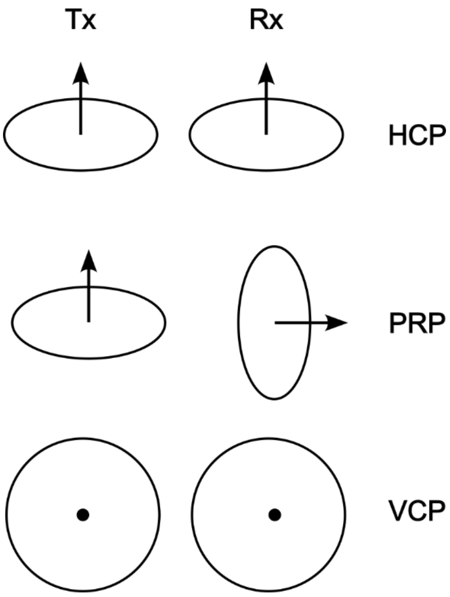

Figure 19: Common coil configurations of FDEM instruments. Figure by author.

The relative weight of a soil layer to the response measured at the receiver coil is a function of its depth (Keller and Frischknecht 1966; McNeill 1980a). This in turn depends on the coil spacing and configuration and thus describes the relative depth sensitivity of a particular instrument configuration. In general, for the QP response, the HCP configuration is most sensitive to deeper soil layers and the uppermost part of the profile has a negligible impact, while the PRP and VCP are most influenced by the upper part of the soil volume (Figure 20). This is a simplified case for a homogenous soil and is more complicated when a multi-layered heterogenous soil with different conductivities is considered. The IP relative response is more complicated (Figure 20), with some depths contributing a negative response for certain coil configurations. It can be seen that the PRP coil has a strong negative response for the very near-surface, while the HCP and VCP configurations have a negligible response for very shallow layers.

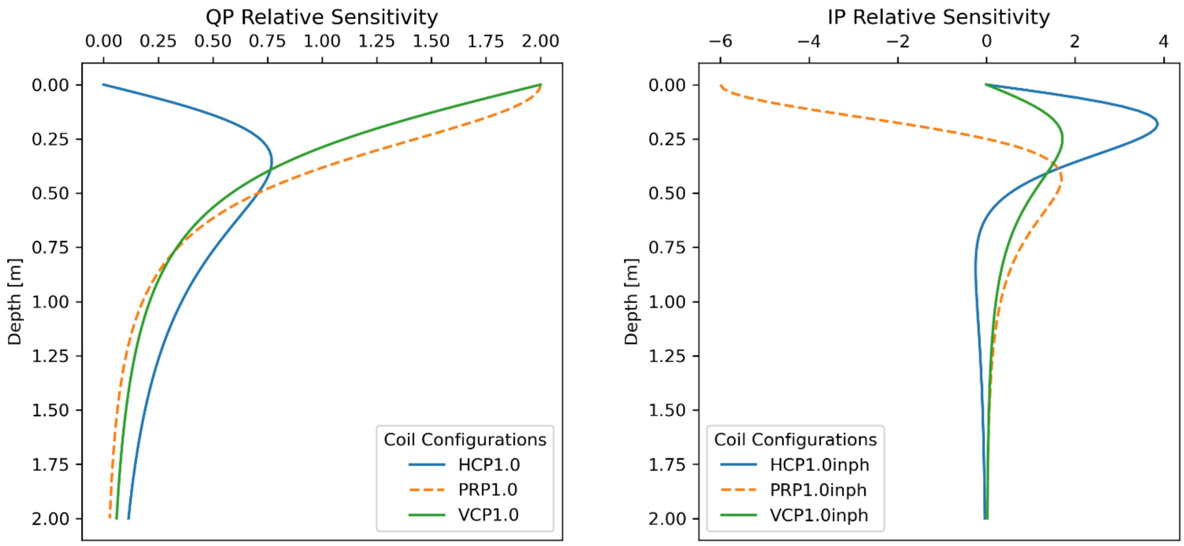

Figure 20: Relative sensitivities for the QP (ECa, left) and IP (MSa, right) responses of different coil configurations with 1 m spacing. Figure by author.

Taking a layered soil into account, it is possible to derive cumulative response functions (separately for the QP and IP response) which integrate the independent individual contributions of separate layers over a given depth range (Wait 1962; McNeill 1980a; McNeill and Bosnar 1999). Again, the HCP configuration has a greater cumulative depth response than the VCP or PRP. The IP response for a given coil pair has a smaller depth of exploration (DOE) than the QP but is more difficult to model in a straightforward manner, given the more complex nature of the cumulative IP response for the HCP and PRP configurations (Saey et al. 2016, p. 42). Cumulative response functions for different coil configurations are considered further below for the specific instrument used. Lastly, the HCP configuration is more sensitive than the VCP to effects of coil misalignment (McNeill 1980a, p. 6), though this is typically not a concern when dealing with fixed coils and short spacings.

A particular aspect of the spatial sensitivity of the IP response of the HCP configuration is that a sign change occurs if a feature is below a given depth (Tabbagh 1986b). Thus, a feature with high susceptibility would return a negative response (compared to the surrounding matrix) if below the critical depth, which is determined by the coil separation. This can result in ambiguous interpretation of HCP IP responses if additional information is not available. If a multi-receiver instrument is used to collect HCP data over several coil distances or with other complementary coil configurations, however, this ambiguous response can provide useful qualitative insight into the depth of features of interest (De Smedt 2013, app. A). Combining HCP and PRP IP responses in interpretations is particularly useful for this reason. Furthermore, the HCP IP response is very stable compared to the PRP which, despite not being subject to the same ambiguous depth-based sign change, suffers from a very low signal to noise ratio.

Magnetometry

In contrast to the active nature of FDEM, magnetometry is a passive method that relies on Earth's geomagnetic field as its energy source. It is the most commonly applied geophysical method in archaeology, owing to its suitability for targeting anthropogenic features, effectiveness over a broad range of geological/pedological conditions, high sampling rate, portability, and development of robust processing schemes and instrumentation. The method measures magnetic flux density (in nanotesla (nT)), largely induced by Earth's field, and identifies local distortions that relate to subsurface features of interest. This field also has a directional component, the separate vectors of which can be measured. Thus, magnetometers are usually classified into scalar/total-field (which measure the total strength of the field) and vector (which measure a particular directional component) types. A number of different sensor types are included within these categories and introductions to the operating principles of these are provided by Aspinall et al. (2008b).

This section will focus exclusively on the fluxgate magnetometer (FM), which is the most commonly employed by archaeologists and the type used throughout this thesis. It is possible to measure the magnetic field at a particular location using only a single sensor but this measurement is more complicated to interpret as it includes the total combined influence of features of interest, in addition to broader low-frequency variations (e.g., geological bodies) and the Earth's magnetic field. Removing the influence of the latter is particularly important as its strength varies significantly with time. These include diurnal variations related to Earth's orbit (the phenomenon of solar wind or the emission of charged particles from the Sun) as well as variations related to nuclear reactions in the sun (magnetic storms) which can range in duration (Aspinall et al. 2008b, p. 31). Because variations of archaeological features (often about 5-10 nT compared to the Earth's field of approximately 50,000 nT) are usually smaller than these variations, it is crucial to remove them.

To account for this external influence, two sensors are commonly used in a variety of configurations. This can take the form of a stationary reference sensor, the observations of which can be subtracted from a roving sensor (variometer mode). More commonly, two sensors are arranged in gradiometer mode at a fixed distance on a particular axis to measure a specific vector of the field. A vertical configuration is typically used, where the measurements from the upper sensor are removed from the lower sensor, thus removing the influence of the Earth's magnetic field. This creates an inherent high-pass filter in the data, removing low-frequency variations and more effectively targeting features of archaeological interest. The height of the sensor above the ground and the distance between the upper and lower sensor have an important effect on the appearance of anomalies. A larger separation between sensors reduces the high-pass filter effect (more blurring) and results in greater sensitivity to deeper/stronger anomalies (by removing less of their influence). A lower sensor height results in better resolution of subsurface (archaeological) targets but also increases the influence of other shallow anomalies such as intrusive metal scatter (Figure 21).

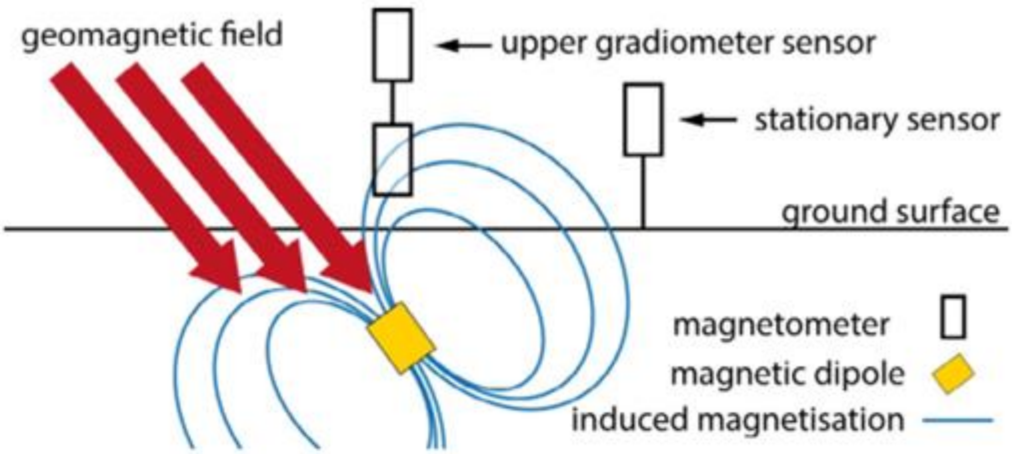

Figure 21: Basic operating principles of magnetometry. A gradiometer configuration is shown, as well as a stationary reference sensor. From Garré et al. (2023, fig. 4), used with permission of copyright holder (Philippe De Smedt).

Fluxgate sensors are typically made of two small primary coils wound in series but in opposite directions around mu-metal cores (Aspinall et al. 2008b, pp. 34–41). Without the influence of an external field, a low-frequency alternating current in the coils will produce equal but opposite magnetic flux in each core. A larger secondary coil around both cores thus has a net zero flux. Following Faraday's law of induction, a changing flux results in an electromagnetic force (voltage) equal to the rate of change of the flux. Thus, the presence of an external magnetic field aligned with the cores produces an output voltage measured at the secondary coil which is proportional to the magnitude of that magnetic field.

Another important consideration for magnetometer data, especially when comparing it to FDEM magnetic susceptibility, is the separate contributions of induced and remanent magnetism. The total measured flux density includes both the induced and remanent component, which are compared to one another through the Koenigsberger ratio (Fassbinder 2015). Determining the magnetic origin of an anomaly can be helpful in ascertaining its function. Examples of induced archaeological magnetic anomalies include topsoil-filled features such as ditches, pits, and postholes while remanent anomalies may include features such as hearth or kilns. Discriminating between the two types of magnetism is not always straightforward, particularly as remanent features also tend to have high magnetic susceptibility, as in the case described above where heating a sample may result in ferrimagnetic enhancement alongside remanent magnetization. In FDEM magnetic data (in the form of in-phase volume susceptibility), remanent magnetism is not recorded and the response includes only the induced component.

Method Selection

FDEM and FM were selected as the primary methods for this research as they are well suited to the pedological/geological conditions encountered (fine-grained loess soils with low/stable magnetic background and relatively low conductivity (i.e., non-saline soils, < 100 mS/m)) and the range of targets of interest (see Chapter 2). This allowed for the recording of distinct electrical and magnetic properties (electrical conductivity, magnetic susceptibility, and magnetic flux density) for a more complete understanding of anthropogenic and natural influences on the subsurface environment. Multi-method surveys are recognized as being particularly important in archaeological prospection, with increasingly sophisticated data integration methods allowing for more robust interpretations of recorded contrasts (Kvamme et al. 2019). Additionally, both methods can easily be deployed in mobile arrays (see below) for large-area prospection at relatively high resolution, a particularly important consideration for the prospection of early modern battlefields.

FDEM simultaneously provides electrical and magnetic datasets, the combined interpretation of which can be useful for understanding recorded anomalies. As anomalies of interest are thought to be represented by a range of both electrical and magnetic contrasts, it was deemed important to implement a methodology providing both types of data. While FDEM surveys necessarily have a coarser sampling resolution (larger sample support and lower spatial sensitivity) than other methods (direct current resistivity or GPR), they are more versatile across a larger range of field conditions. No direct contact with the ground is required, as is the case with resistivity, allowing for greater efficiency in survey (no limitations due to contact resistance). A multi-receiver instrument with multiple coil configurations (detailed below) was also used to provide a vertical dimension and different spatial sensitivities. A small trial direct current resistivity profiling survey was also undertaken to allow for comparison with an FDEM dataset.

The effective use of GPR was generally precluded by the relatively high conductivity of the soil in the study area (predominantly silty deposits, with median bulk conductivity values of around 20 mS/m according to FDEM ECa). Additionally, the rolling terrain complicates topographic corrections (for depth) over large areas and the generally uneven surface (from ploughing) results in inconsistent coupling between the instrument and ground. Small trial GPR surveys were, however, undertaken to assess their performance. FM was selected for its ability to provide a higher sampling resolution and sensitivity compared to FDEM, as well as a distinct but complementary magnetic dataset (as detailed above) to be analyzed in conjunction with the FDEM data. The high resolution and sensitivity of the FM configuration allowed for particular targeting of anthropogenic (i.e., including archaeological) influences.

Instrumentation, Survey Design and Data Processing

FDEM surveys were undertaken with a DualEM-21H sensor (DualEM, Canada), which is equipped with a transmitting coil operating at 9 KHz and three pairs of receiving coils (three coplanar to the transmitter at 0.5, 1, and 2 m spacing and three perpendicular at 0.6, 1.1, and 2.1 m) (Figure 22). This instrument is well-established as an effective prospection tool for a wide-range of archaeological and environmental features (De Smedt, Saey, et al. 2013). The sensor has a factory-set sampling rate of 8 Hz. The instrument was deployed in HCP mode, rather than VCP. This decision was made in order to take advantage of the deeper relative and cumulative depth response of the former, whereas the latter has a depth response that is more similar to the PRP configuration. Additionally, the sign change in the IP response of the HCP coil configurations at critical depths allows for a qualitative assessment of depth when combined with the responses from other coil pairs, as described above. These critical depths are 0.3 m, 0.6 m, and 1.2 m for the 0.5 m, 1 m, and 2 m HCP coils respectively. For shorthand, the coil configurations will be referred to as HCPH/HCP1/HCP2 and PRPH/PRP1/PRP2 throughout this thesis with the relevant signal component appended (e.g., HCP1IP referring to the in-phase component of the 1 m horizonal coplanar configuration).

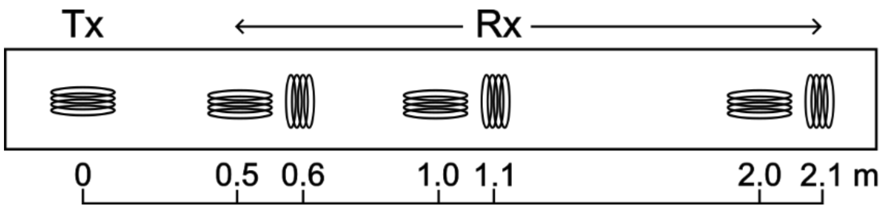

Figure 22:Coil configurations of the DualEM-21H. Figure by author.

Relative depth responses (QP and IP) for each coil pair of the DualEM-21H are shown in Figure 23. Note how the peak weights and shape of the curves change with increasing coil separation. Table 2 lists the DOE for each coil pair. For the QP response, this is conventionally taken to be the depth at which 70% of the cumulative response is registered, as shown in Figure 24. The HCP pairs integrate a significantly larger soil volume (up to >3 m for the HCP2 pair), approximately three times that of the corresponding PRP pair. As previously noted, the complex shape of the response curves for the IP signal precludes this 70% delineation. Thus, the depths of investigation for the IP response are approximations (De Smedt, Saey, et al. 2014; Saey et al. 2016; De Smedt et al. 2022).

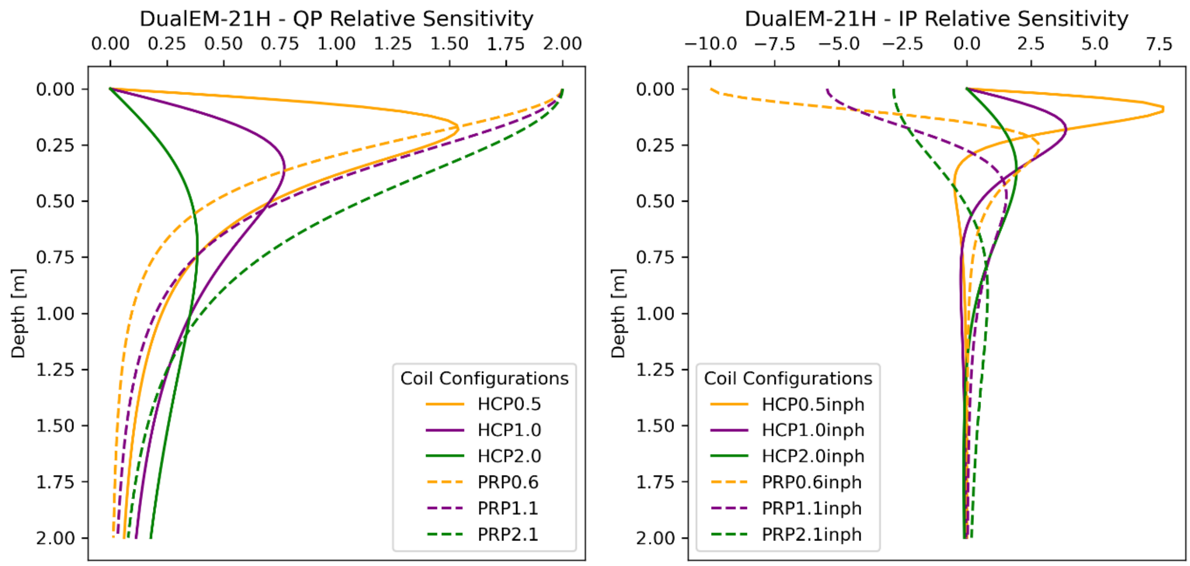

Figure 23: Relative sensitivity functions for the DualEM-21H sensor. Figure by author.

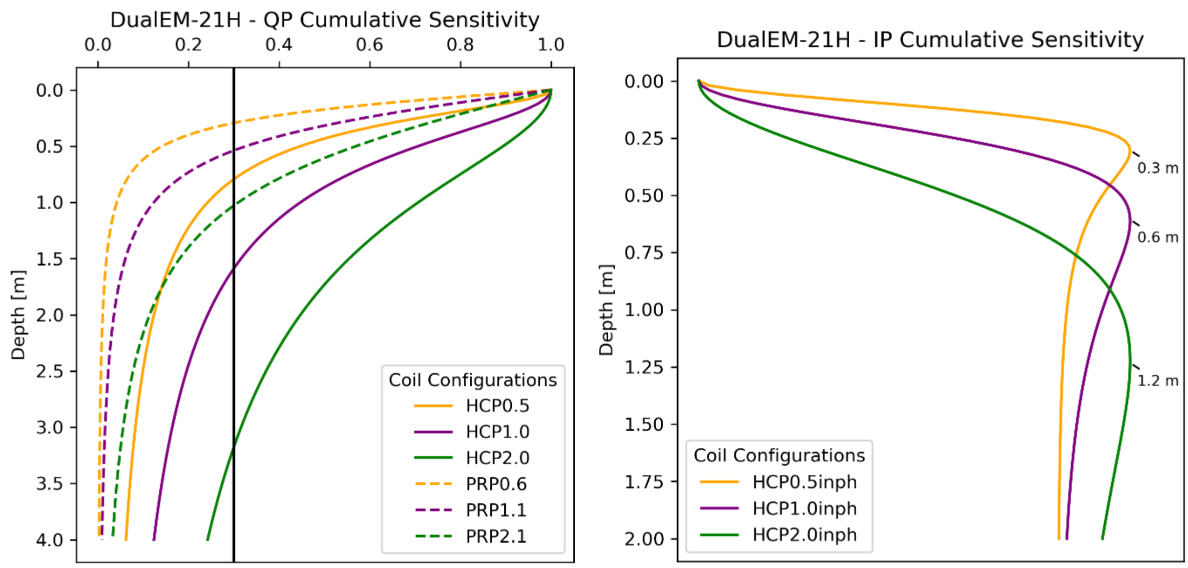

Figure 24:Cumulative response functions for the DualEM-21H sensor. The vertical black line for the QP responses shows the 70% DOE. The annotations for the IP responses indicate where the sign change occurs. Figure by author.

Table 2: Approximate depths of exploration for each coil configuration and response type of the DualEM-21H sensor.

	QP (ECa)	IP (MSa)
HCP – 0.5 m	0.8 m	0.5 m
HCP – 1 m	1.6 m	1 m
HCP – 2 m	3.2 m	1.5 m
PRP – 0.6 m	0.3 m	0.3m
PRP – 1.1 m	0.5 m	0.6 m
PRP – 2.1 m	1.0 m	1.2 m

FM surveys were performed using Sensys FGM650/8 (Sensys GmbH, Germany) sensors, a single-axis fluxgate type with a vertical separation of 0.65 m in gradiometer configuration. This instrument has been widely and successfully used in archaeological prospection (Note, Saey, et al. 2018; Pickartz et al. 2019; Stele and Linck 2024). An array of five sensors, each with a sampling rate of 100 Hz, was used for increased efficiency. Fluxgate sensors are very well established and are the most commonly used type in archaeological prospection, thus allowing for easier comparison with a range of other prospection datasets. While there may be some benefit to the use of other higher-sensitivity magnetometers (caesium and other alkali vapour types, particularly in the low-noise loess environment of Waterloo, such a comparison was beyond the (time and financial) scope of the current project.

Both measurements were performed in mobile configurations with the instruments towed behind a utility quad bike. Data was collected along parallel lines with a bidirectional pattern. For the FDEM sensor, this was accomplished using a metal-free sled with the instrument 0.16 m above the ground surface and 3.45 m behind the towing vehicle (Figure 25). The FM sensor array was towed using a cart and towbar system composed of a variety of non-ferrous materials (aluminum, brass, wood) (Figure 26). Sensors were mounted approximately 0.20 m above the ground surface, though this varied somewhat depending on the surface vegetation. Spatial information was recorded using differential GPS with RTK corrections (typical accuracy <10 cm) supplied via mobile network, synchronized to instrument readings with timestamps. For the FDEM setup, the GPS sensor is mounted on the quad bike and a lightbar guidance system (Trimble AgGPS EZ-Guide Plus) connected to the GPS was used to maintain direction along each survey transect. For the FM, the GPS is mounted above the central sensor in the instrument array.

Figure 25: Mobile survey configuration for FDEM surveys. Photo by author.

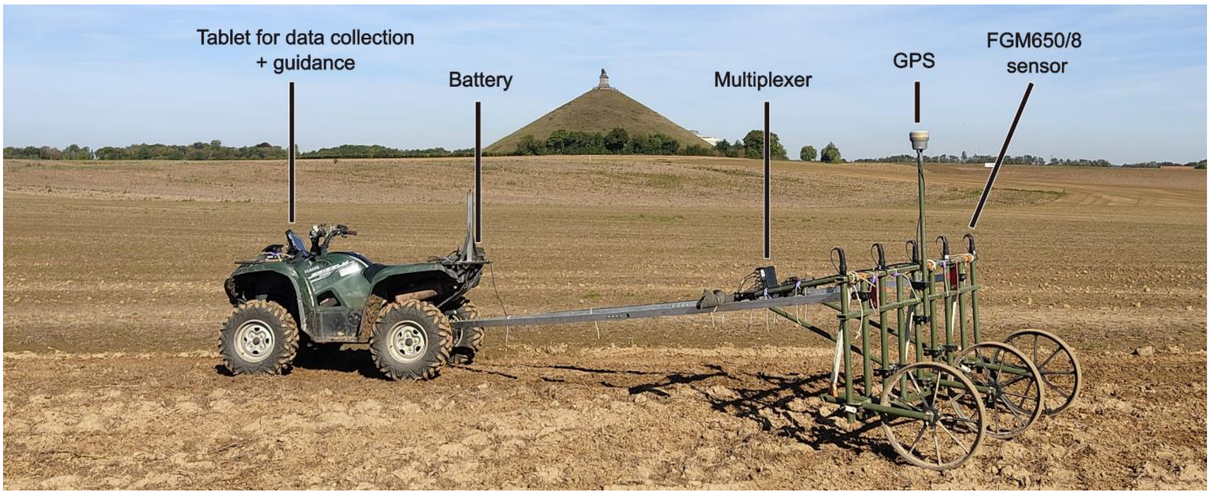

Figure 26: Mobile survey configuration used for magnetometry surveys. Photo by author.

Interline spacing of 2 m was used for the FDEM surveys[11] to provide a good balance between survey speed and sampling density. This allows for mapping pedological variations with high resolution, while also targeting larger archaeological features (e.g., a feature with a diameter of >4 m would be crossed by at least two survey lines[12]). In-line sampling was approximately 0.25 m with a survey speed of 10 km/h. The influence of different inter- and inline sampling intervals for FDEM data is considered by Hanssens et al. (2021) for both synthetic and real examples. FM surveys were undertaken with an interline (sensor array) spacing of 0.5 m, thus allowing for a greater sampling density and the resolving of smaller features. This traverse interval is considered to be a good compromise between survey speed and individual feature discrimination (Schmidt et al. 2015, p. 64). The depth of a magnetic anomaly also influences its width: the size of the anomaly is considered to be represented by its width at half the maximum amplitude (Schmidt and Marshall 1997, p. 2). Thus, it follows that shallower features will require denser sampling. A rule of thumb has been suggested whereby the sampling intervals should not exceed the dimensions or depth of the feature (Aspinall et al. 2008b, p. 112). While 1 m interline spacing was considered to be the standard sampling interval as recently as a couple decades ago (Gaffney and Gater 2003, p. 95), it is now much more common to see 0.5 m or even 0.25 m. In-line sampling was set to 0.15 m during processing (the 100 Hz sampling rate providing an unnecessarily dense in-line sampling).

Data processing was undertaken using software developed at the ORBit research group, Ghent University. This workflow is described elsewhere for FDEM data (Delefortrie et al. 2014; Hanssens et al. 2021) and will not be described at length here but essentially consists of correcting for time lag between sensor and GPS data, removing the influence of signal drift, converting raw instrument output to apparent electrical conductivity (ECa), and interpolating the data to a continuous surface. Interpolation was undertaken to a 0.5 m raster grid using inverse distance weighting (IDW) (Rouault et al. 2024):

$$Z = \frac{\sum_{i=1}^{n} \frac{Z_i}{r_i^p}}{\sum_{i=1}^{n} \frac{1}{r_i^p}}$$

where:

- Z = calculated value at grid node
- Z_i = known value at point i
- p = weighting power (here, 2)
- n = number of points in search radius (here, a radius of 3 m was used with a maximum of 11 neighbours)

[11] Interline spacing of 1 m was used in some of the early surveys but a decision was made to switch to 2 m considering targets of interest, for increased efficiency and due to redundancies observed with the FM data. See Chapter 4 for further discussion and comparative datasets (e.g., Figure 32 and Figure 36).

[12] This is a derivation of the Nyquist-Shannon sampling theorem from signal processing, which defines the sampling rate at which a function with a given maximum frequency (or minimum wavelength) can be resolved (Schmidt, Dabas, et al. 2020, p. 9).

IDW is a very efficient interpolation algorithm that assigns weights to points within a search area based on their proximity to the desired location but has the downside of introducing some in-line streaking due to the increased sampling distance in this direction compared to the interline spacing. Other more computationally intensive methods (e.g., natural neighbour (NN) or kriging) are available which take the spatial structure of the samples into account, including measures of autocorrelation, and vary the assigned weights accordingly (Webster and Oliver 2007). The effect can be seen when comparing IDW with NN (Sibson 1981) interpolations for a subset of the dataset in Figure 27. While this results in a small but noticeable cosmetic improvement (particularly for linear features), the sampling density in this case is high enough that it does not have a serious impact on visual interpretation. For asymmetric (perpendicular) coil combinations in particular, this also does not resolve all of the streaking/staggering effects which are introduced due to heading errors associated with anisotropy and bidirectional data collection (Hanssens et al. 2021). The anisotropy effect can be accounted for with the collection of repeating survey lines and additional processing (ibid) but was not undertaken here as, again, the effect on visual interpretation was deemed to be fairly minimal compared to the additional effort required during data collection. Lastly, to produce a coherent global merged dataset after interpolation, edge-matching was used to account for offsets caused by seasonal soil moisture variation in the QP data while median levelling was used to compensate for instrument noise in the IP data.

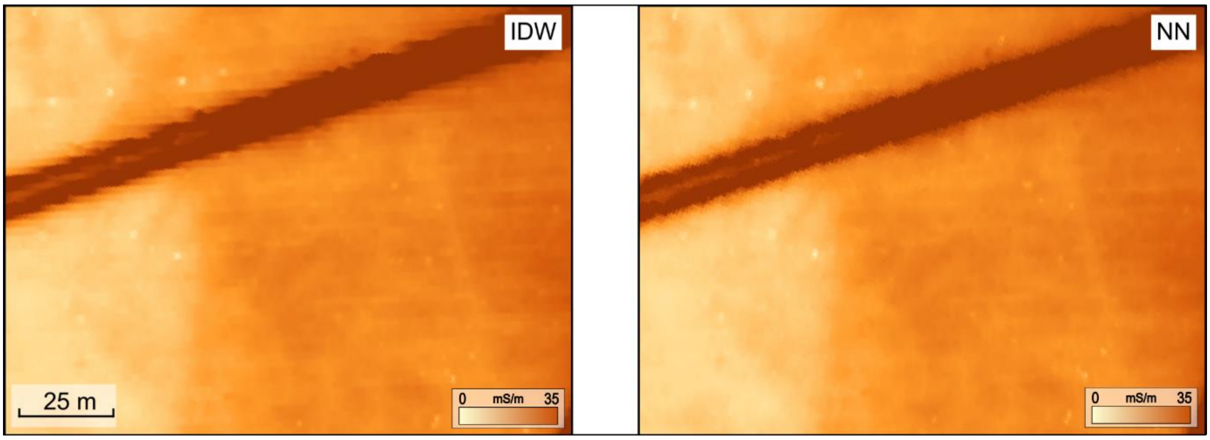

Figure 27: Comparison of IDW (left) and NN (right) interpolations for an HCP1QP dataset. Figure by author.

Processing of the FM data was minimal and consisted of removal of superfluous in-line data (adjacent points closer than 0.15 m), levelling of sensor data through removal of each transect median, and interpolation to a 0.1 m grid using the IDW method. The influence of IDW artefacts in the interpolation (in-line streaking) is less apparent here because of the greater sampling density compared to the FDEM dataset.

In all, a total of approximately 90 ha[13] were surveyed with both methods across a total of five months (late June – late November 2022). Combined with additional FDEM surveys completed between 2014 and 2017 (De Smedt 2017), the total sample size is just over 100 ha, equating to nearly 10% of the battlefield's surface area. While selection of survey parcels was ultimately governed first by

[13] This also includes approximately 10 hectares surveyed at the battlefield of Quatre Bras some 10 km to the south, where an engagement between the Anglo-Allied and French forces took place two days prior to Waterloo. This data will, however, not be further considered for this thesis as it was not possible to conduct any validation sampling.

landowner willingness and then by access dictated by landuse (see below), a form of stratified sampling was employed. Thus, an attempt was made to sample parcels from a range of different activity areas across the landscape. This includes areas along and on either side of Wellington's main ridge position, points of land in proximity to the fortified farmhouses, the ridge along which Napoleon's troops were deployed, and the hinterland of the village of Plancenoit where the action with the Prussians was concentrated. This resulted in a noncontiguous dataset scattered widely across the protected battlefield landscape.

Small trials were also made with two other geophysical techniques, ground penetrating radar (GPR) and electrical resistivity tomography (ERT), to assess their potential for targeting particular features of interest. As previously introduced, GPR is a commonly used method in archaeology that uses high-frequency electromagnetic waves to map interfaces of varying dielectric permittivity in the subsurface (Jol 2009). ERT is a specific configuration of the resistivity technique, whereby apparent electrical resistivity is calculated (usually along a 2D transect) using a series of electrodes that inject current and measure resulting potentials (Schmidt 2013).

GPR was used in two areas where clear magnetic anomalies linked to archaeological features were recorded. A GSSI UtilityScan DF (Geophysical Survey Systems, Inc., USA) instrument with a dual-frequency antenna (300/800 MHz) was used in a manual cart configuration with a GPS unit (with RTK corrections as described above). A 10 x 10 m grid was surveyed in two orthogonal directions using 25 cm cross-line and 1 cm in-line spacing. Processing was undertaken using gprPy (Plattner 2020) as follows: time zero correction, automatic gain control, dewow, and mean trace removal. Estimates of subsurface wave velocity for the conversion of time to depth were made using measured dielectric permittivity values (with a HydraProbe coaxial impedance dielectric reflectometer probe) converted to velocity (following Conyers 2013, eq. 3.1). These estimates were also confirmed through hyperbola fitting and found to be very accurate.

ERT profiles (Terrameter LS, ABEM, Sweden) were recorded over two transects where colluvial deposits were identified to allow for comparison with FDEM ECa data from the same locations. Electrode spacing of 1 m was used in a multi-gradient array (Aizebeokhai and Oyeyemi 2014). Processing was undertaken using ResiPy with default inversion settings (Blanchy et al. 2020).

Practical Considerations for Large-Scale (Terrestrial) Surveys

As previously noted, battlefield sites tend to have a much larger surface area than many typical archaeological sites. As a result, the scale of investigation must be extended beyond the site or field scale to the level of the landscape. While many early geophysical applications in archaeology were relatively small in scale (perhaps a few hectares) and employed manual survey techniques, recent advances in vehicle-towed sensor configurations and processing capabilities have now made large-scale surveys (in the order of tens up to hundreds of hectares) commonplace (Trinks 2015). Thus, at present, other practical considerations around landuse and access to large areas of land (rather than technical hurdles or human effort required for manual survey) are the main limiting factors for ground-based geophysical surveys, particularly in regard to arable landscapes where the majority of this work takes place around the world.

This has a significant influence on the planning and execution of large-scale geophysical surveys, impacting the design and characteristics of the sample. In the case of the battlefield of Waterloo, the vast majority of the land area is presently dedicated to agriculture. As such, it is inaccessible to vehicle-based survey for large portions of the year. This necessitates a strategy whereby survey must be undertaken on an ad hoc basis, taking advantage of narrow windows of time when access is possible.

The Battle of Waterloo took place over an area of approximately 1,200 ha, much of which has been protected by law since the early 20th century. Of this, just under 1,000 ha (83%) is classified as agricultural (Service public de Wallonie 2018). An additional 38 ha is classified as wooded and 133 ha as residential, making them inaccessible to motorized survey. Another small portion (totaling approximately 20 ha) is classified as transportation networks, commercial/industrial, or recreational and is similarly inaccessible.

The agricultural land is highly fragmented and managed by a combination of freehold and tenant farmers. Navigating this web of ownership and land management is a time-consuming endeavour that must evidently take place before any survey work. Upon securing permission from the appropriate landowners and managers to survey a particular parcel, it was then necessary to wait for an appropriate time to survey. In the case of an agricultural parcel, this typically meant waiting until the field was crop-free (i.e., after the harvest of one crop and before the sowing of the next one). This window can be very limited and is complicated by any tilling that might also take place. Where deep tilling or ploughing is undertaken in advance of sowing, survey may not be possible (or if it is, data quality will suffer from sensor instability). In some cases, it was possible to survey fields where green manure (e.g., mustard) had been planted for nitrogen fixation, although there are constraints on the timing of this as well as it must typically only be done as close to the subsequent ploughing as possible. In this regard, landowners also have different preferences with some preferring survey to take place shortly after sowing of the green manure crop and others preferring that survey occur once the crop has grown sufficiently (i.e., shortly before ploughing). This is also largely dictated by land management policies, which determine when the nitrogen-fixing crop may be ploughed into the soil (Gouvernement de Wallonie 2014).

Survey opportunities and timings are spread out considerably over the course of the year depending on the type of crop, which will typically rotate for a given field. Thus, harvest begins in the summer (winter wheat/barley) and continues through the autumn (corn, potatoes) and early winter (sugar beet). This necessitates a piecemeal survey approach over an extensive period of time.

Another landuse consideration is hunting, which in Belgium is closely linked to land ownership (with hunting rights typically being purchased by an association of shareholders). A considerable amount of hunting takes place on or immediately adjacent to agricultural land and this represents another constraint to survey.

With pastureland (which comprises a much smaller surface area than arable land throughout the study area), timing for field access is more flexible but requires either negotiating access at a time when animals are not present or performing the survey in the presence of the animals. For fallow fields or meadows managed for fodder, the window of opportunity is less restricted but access must typically wait until the vegetation is cut. Even if access before the cutting is possible, the vegetation height can have an impact on the quality of the data (Aspinall et al. 2008b, p. 92).

In sum, terrestrial geophysical surveys on agricultural land encounter significant challenges when attempting to deploy across large areas of the landscape in relatively short periods of time. These issues are now more pertinent due to the widespread use of mobile instrument configurations which have greatly increased survey rates. Careful planning over an extended (i.e., multi-month or multi-year) survey campaign is required to achieve maximum coverage. Prioritization of certain parcels over others will likely be necessary as small windows of overlapping harvest will not allow sufficient time for survey within a single season. A considerable degree of flexibility is also required to adapt to dynamic crop cycles, which are largely driven by meteorological variation.

Achieving complete survey coverage of the archaeological landscape at Waterloo would take several years following the stepped survey approach described above. While this particular site has the benefit of long-term legislative protection (a luxury that many similar sites do not have), it is nevertheless still menaced by threats such as soil erosion and illicit artefact hunting. Combined with the fact that most projects are limited to much shorter research periods, there would be great benefit to the development of even faster and less invasive forms of geophysical survey.

The increasing use of low-altitude uncrewed aerial vehicles (UAVs) for geophysical survey holds great potential for increasing the efficiency of large-scale geophysical surveys. Airborne surveys have long been widely used in other geophysical applications for large-area coverage but these generally lack the resolution required for archaeological purposes. It has been suggested that UAV surveys may help to bridge the gap between terrestrial surveys (with low coverage but high resolution) and traditional crewed airborne surveys (with high efficiency/coverage but low resolution/signal strength) (Zheng et al. 2021). Recent successful case studies deploying low-altitude sensors, many of which use commercially available UAVs, have shown the possibilities of these methods in archaeology (Linck and Kaltak 2019; Schmidt, Becken, et al. 2020; Schmidt and Coolen 2021; Stele et al. 2022). There are still some issues to be resolved (particularly around achieving sufficiently high sampling density, acceptable signal-to-noise ratios and appropriately long flight times), but this evidently holds great potential for alleviating many of the challenges around limited access to agricultural fields discussed above, as well as other types of challenging terrain for mobile survey (forested areas, steep slopes, etc.).

Chapter 4: Contributions of Multi-Method Geophysical Survey to Archaeological Research at the Battlefield of Waterloo

This chapter is based on a paper published in *Archaeological Prospection*. Modifications here include a reduced background to Waterloo and the geophysical survey methodology, insertion of GPR data/discussion, expanded overall discussion, and several additional figures/examples.

Williams, D., Bosquet, D., Pollard, T., Welham, K., Eve, S. and De Smedt, P., 2024. Contributions of Multi-Method Geophysical Survey to Archaeological Research at the Battlefield of Waterloo. *Archaeological Prospection*, 31 (3), 267–287. https://doi.org/10.1002/arp.1952

Introduction

As previously noted, advances in geophysical instrumentation and processing in recent decades have enabled the prospection of increasingly large areas, marking a particularly important development for the investigation of large archaeological landscapes (Darvill et al. 2013; Trinks 2015; De Smedt et al. 2022). Nevertheless, large-scale geophysical surveys of battlefields have remained relatively rare. This chapter presents data from large-scale multi-method surveys at the battlefield of Waterloo, Belgium representing, to the author's knowledge, the largest dedicated geophysical survey undertaken at a single battlefield site. The outcomes of the survey are considered, with respect to a set of defined targets (see Chapter 2), and some of the challenges associated with the collection and interpretation of data from (early modern) battlefield sites are considered.

Research Context

Despite the historical significance of the site, professional archaeological research at Waterloo had been very limited until quite recently. This is partly due to the fact that the majority of professional archaeological work in Wallonia takes place in the framework of preventive archaeology. The battlefield has been legislatively protected from large-scale disturbances since the early 20th century; thus, there was no pressing need for archaeology in this context. Furthermore, there was still a belief that archaeology could only minimally contribute to an event that has been the subject of such intensive historical research (Waterloo Uncovered 2021, p. 3). Beginning in 2012, however, developments at the site associated with the bicentenary and construction of visitor infrastructure necessitated archaeological intervention. A major finding from this work was the discovery of the isolated burial of a Hanoverian soldier (Bosquet et al. 2014). Afterwards, beginning in 2015, Waterloo Uncovered has undertaken systematic archaeological work at several important areas across the battlefield including Hougoumont, Mont-Saint-Jean, Plancenoit, and Fichermont (Waterloo Uncovered 2015b; Bosquet et al. 2016, 2017; Moulaert et al. 2019; Moulaert, Bosquet, et al. 2020).

While the battle has been extensively researched (perhaps more so than any other conflict) and hundreds of books have been written about it, many questions remain unresolved (Adkin 2001, sec. 10). Archaeological research has the potential to shed light on some of these events. The broad aims of archaeological research at Waterloo are thus in line with those of battlefield archaeology more generally: to use material remains to reconstruct aspects of the conflict and particularly the experiences of participants poorly reflected in the documentary record. More specifically, research questions relate to the accuracy of contemporary maps and drawings, the degree of archaeological integrity remaining in the heavily metal-detected landscape, the search for evidence for the disposal of the dead (to date extremely limited despite extensive casualties (Pollard 2021)), and the impact of modern landuse (especially soil erosion worsened by mechanized agriculture) on the preservation of ephemeral archaeological features. Much of the work to date has focussed on the farms of Hougoumont and Mont-Saint-Jean, key elements of the Anglo-Allied position functioning as a fortified bastion and field hospital, respectively. Key research questions and findings relating to specific events at these locations are detailed elsewhere (Eve and Pollard 2020; Bosquet et al. 2023).

Geophysical surveys were undertaken at a very early stage of the Waterloo Uncovered project[14], focussing on the immediate area around Hougoumont (De Smedt 2017). These pilot efforts indicated that the site was well-suited to non-invasive prospection but that the identification of specific features related to the battle remained challenging because of the complicated influences of earlier and later landuse. Nevertheless, the encouraging results of these early trials prompted a larger project to expand the scope of the surveys (Figure 28).

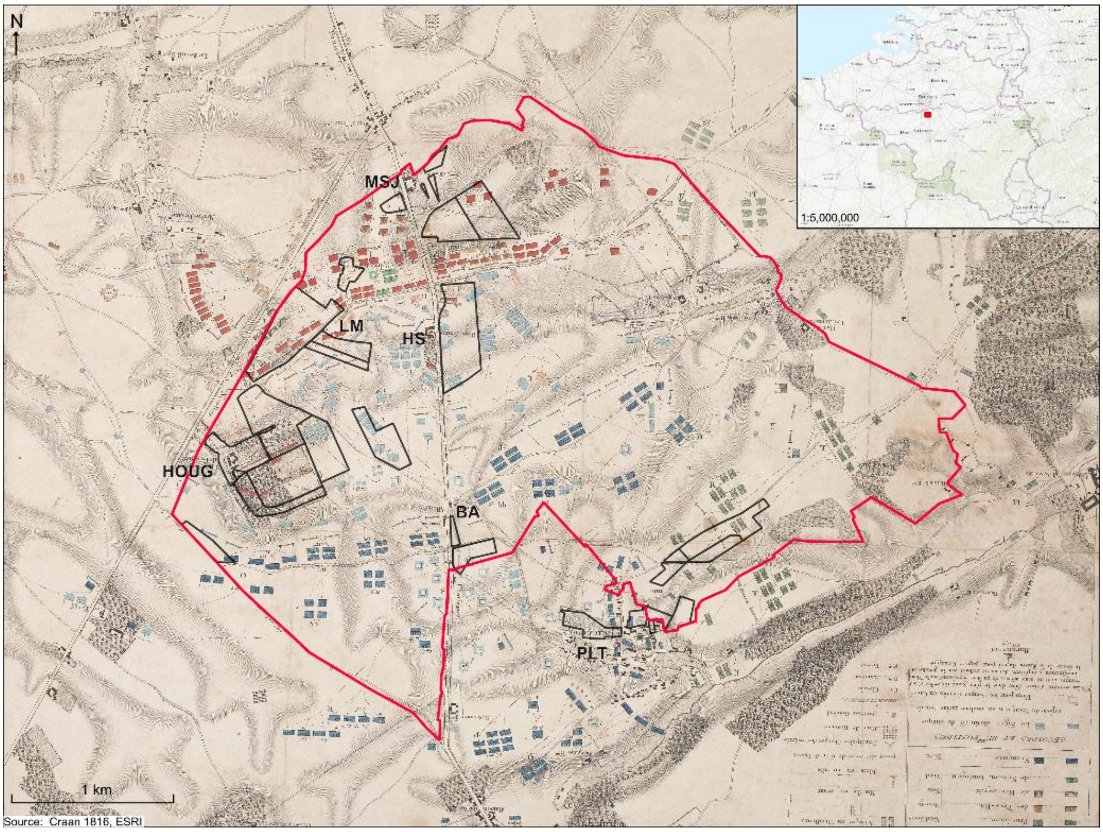

Figure 28: Overview of battlefield on 1816 map, showing Anglo-Allied (in red at top), French (in blue at bottom) and Prussian (in green, lower right) deployments. The red boundary marks the zone under legislative protection. Survey areas outlined in black. Basemap : Plan du Champ de Bataille de Waterloo*, W.B. Craan, 1816 (British Library). Annotated locations mentioned in text:* Hougoumont Farm (HOUG), Lion Mound (LM), Haye Sainte

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[14] Note that some geophysical surveys (including GPR, FM, and resistivity) were also undertaken by Tim Sutherland in the Hougoumont area prior to the commencement of the Waterloo Uncovered project (Sutherland 2016); this data is not considered herein.

Farm (HS), Mont-Saint-Jean Farm (MSJ), Belle Alliance (BA), Plancenoit (PLT). Basemap from *British Library Collections, Item 31885, no copyright restrictions. Figure by author.*

Metal detection using conventional (very low frequency induction balance) detectors (Overton and Moreland 2015) has been a central component of the work at Waterloo, following the principles established during early battlefield surveys in the United States (Scott and McFeaters 2011, pp. 108–110). Alongside this work, more traditional forms of archaeological excavation have explored other features. Other types of large-area geophysical survey may hold particular potential for bridging the gap between these approaches. While the conventional metal detector is of course itself a geophysical instrument, it is limited in depth of exploration, range of identifiable targets, and efficiency for large-area surveys. Meanwhile, excavation and other sampling approaches provide detailed archaeological data on features of interest but are of limited use for prospection, particularly in the extensive landscape of Waterloo.

Many of the archaeological targets at battlefields have contrasting geophysical properties which may enable their detection. In the following chapter, this range of targets – metal artefacts, burials, field fortifications, encampments, other anthropogenic terrain, and relevant environmental information – are considered following the framework presented in Chapter 2 with specific reference to large-scale geophysical datasets from Waterloo. This is accompanied by a discussion of limitations and difficulties encountered (related to instrumentation, pedological/geological conditions, or formation/preservation processes).

Methods

The two primary methods used were frequency-domain electromagnetic induction (FDEM) and fluxgate magnetometry (FM), as described in Chapter 3. For the FDEM surveys, a multi-receiver DualEM-21H sensor (DualEM, Canada) was used with a pair of receivers (HCP and PRP) at 0.5, 1, and 2 m from the transmitter. The QP component is proportional to the apparent electrical conductivity (ECa) in a low-induction number (LIN) environment (McNeill 1980a) such as Waterloo, while the IP component is related to apparent magnetic susceptibility (MSa). A transect interval of 2 m (with 0.25 m in-line spacing) was used to target large archaeological features and pedological variability. The FDEM dataset covers approximately 105 hectares (Figure 29, Figure 30).

FM surveys were performed using Sensys FGM650/8 (Sensys GmbH, Germany) sensors, a single-axis fluxgate type with a vertical separation of 0.65 m. An array of five sensors spaced 0.5 m apart was used (with in-line sampling of approximately 0.1 m). The FM dataset covers approximately 80 hectares (Figure 31). For both instruments, measurements were performed in mobile configurations with the instruments towed behind a utility quad bike.

FDEM and FM were selected for their ability to provide complementary datasets and detect a wide range of potential features based on the combination of magnetic and electrical properties. Both are also very efficient for covering large areas in mobile configurations. Given the low magnetic susceptibility of the loess soil background and general lack of substantial electromagnetic noise, both methods were deemed to have a high chance of success at identifying archaeological features of interest. Ground-penetrating radar (GPR) was thought to have a lower chance of success due to the relatively high conductivity of the fine silty soils and the anticipated poor ground coupling associated with the uneven (ploughed) surface but was trialed in select instances. Surveys were undertaken in two areas over previously identified anomalies of interest to preliminarily assess the capability of GPR survey at Waterloo.

Borehole sampling was also undertaken to provide a better understanding of the observations in the sensor data. Sample locations were selected based on visual interpretation with the aim of sampling a representative range of contrasts in all three datasets (FDEM ECa/MSa and magnetometry). This also included locations thought to represent natural soil variability or geological features. A combination of Edelman/Dutch (⌀ 10 cm) and gouge (⌀ 2.5 cm) augers were used in most cases. The gouge auger provides a relatively undisturbed but narrow profile and was often used for preliminary assessment. For collection of larger samples and more comprehensive photography, the larger Edelman auger was used. Soil descriptions were undertaken at all boreholes with photographs of representative profiles. Samples were collected for further analysis of magnetic susceptibility where necessary. This was undertaken using the MS2B dual frequency sensor (Bartington Instruments, UK) for mass specific measurements. Downhole magnetic susceptibility profiles were also recorded at certain locations to assist in the interpretation of the geophysical data. For these, a gouge auger and a Bartington MS2H sensor (Bartington Instruments, UK) were used, with readings taken at every 10 cm. A total of 72 locations were sampled across all major zones of the study area. While access to certain parcels was not possible at the time of sampling due to landuse constraints (see Discussion section), the sampling was deemed to be sufficiently representative.

Limited test excavations were also undertaken as part of the Waterloo Uncovered field campaigns in 2022 and 2023. Features from the geophysical datasets having particularly high archaeological potential were targeted. This results of this work are fully reported on elsewhere (Bosquet et al. 2023), and the major findings will only be summarized here with a particular focus on the geophysical interpretations of features encountered. Exposed plans and profiles were also sampled to collect *in situ* measurements of relevant properties. Magnetic susceptibility was recorded with the SM30 meter (ZH Instruments, Czechia) and conductivity/permittivity with the HydraProbe coaxial impedance dielectric reflectometer probe (Stevens, USA).

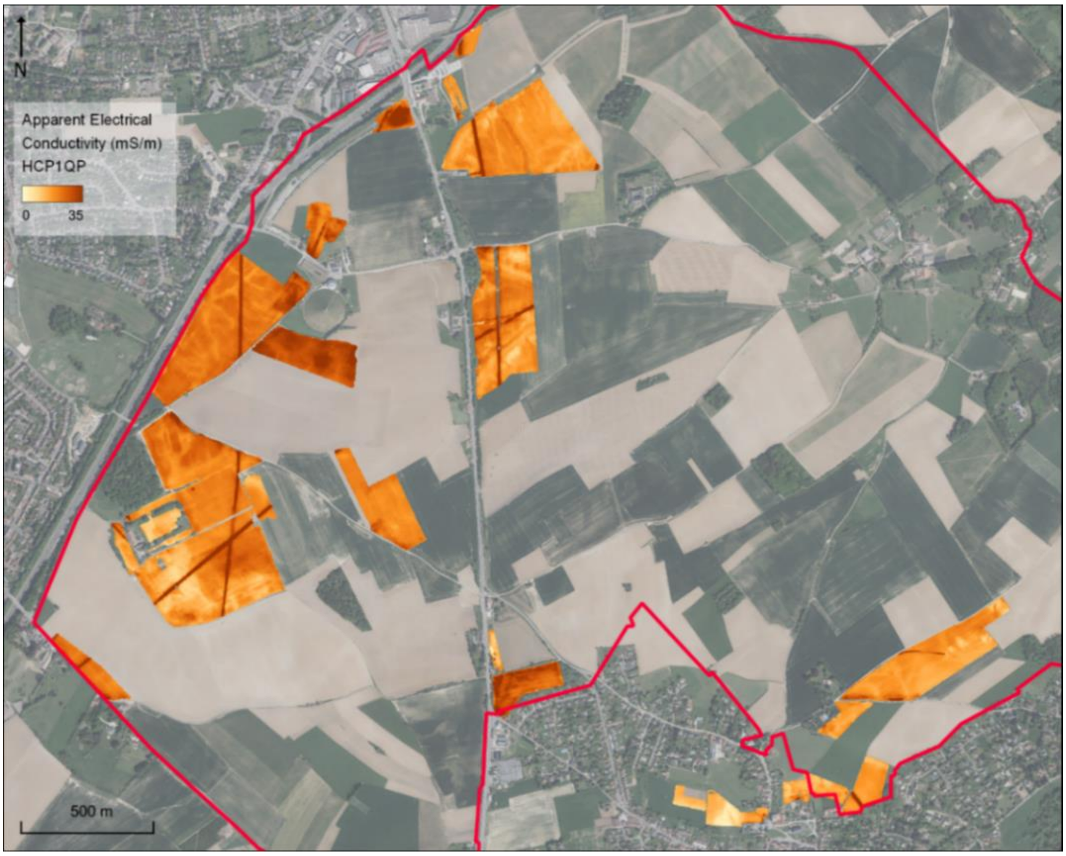

Figure 29: Overview of QP component of FDEM dataset (apparent electrical conductivity) for HCP1 coil pair. Orthophoto basemap (2022) from Géoportail de la Wallonie. Figure by author.

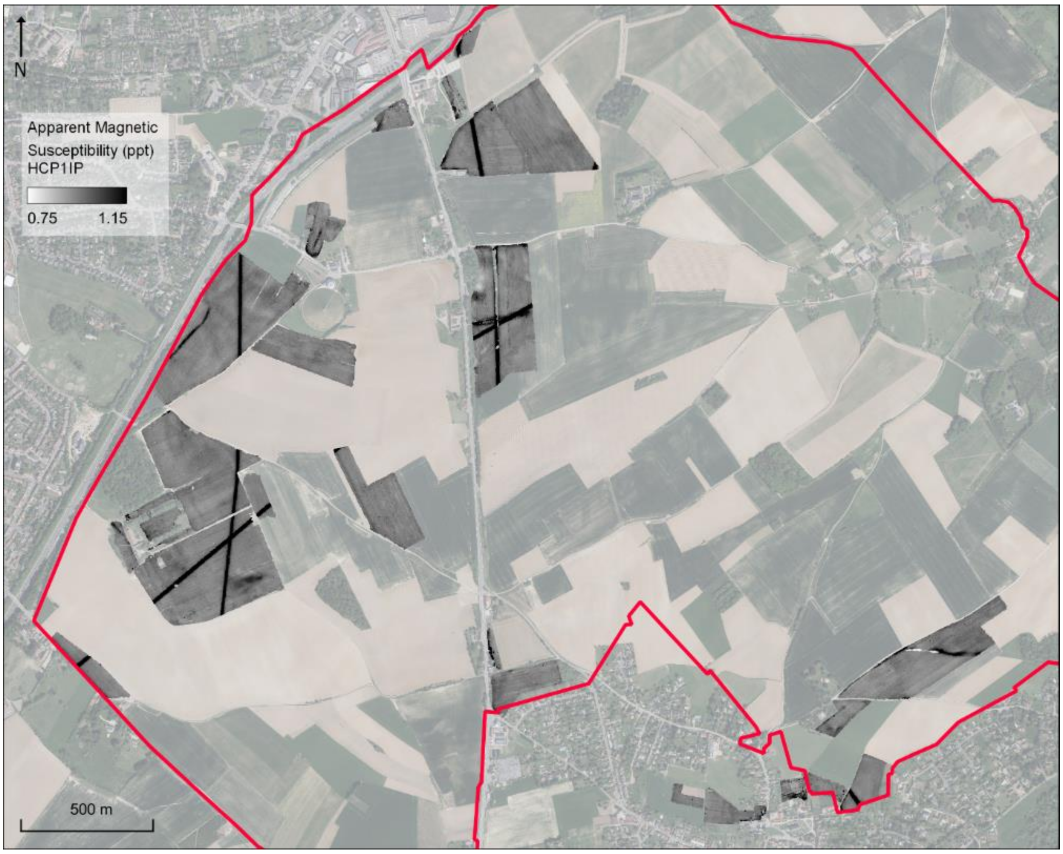

Figure 30: Overview of IP component of FDEM dataset (apparent magnetic susceptibility) for HCP1 coil pair. Orthophoto basemap (2022) from Géoportail de la Wallonie. Figure by author.

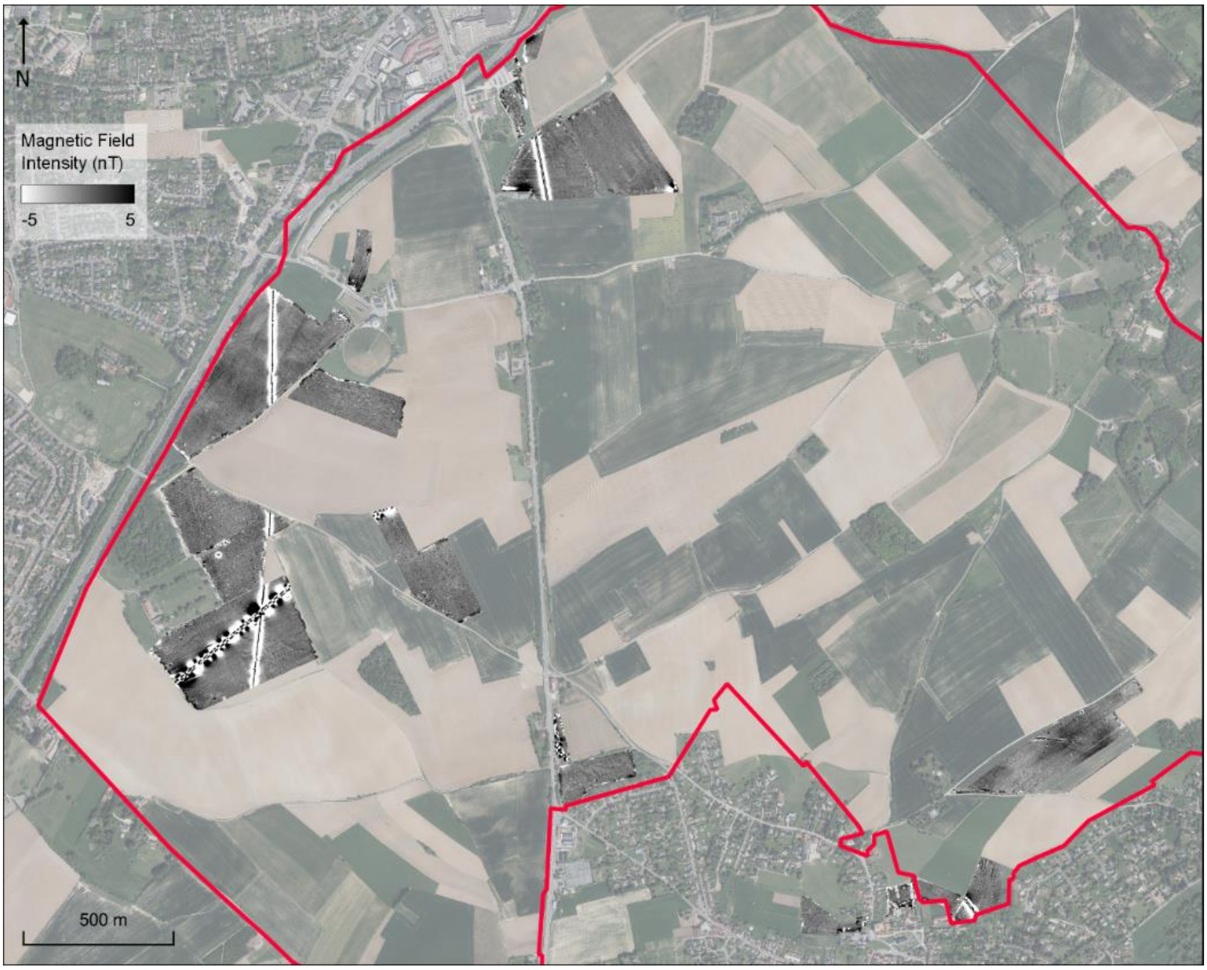

Figure 31: Overview of magnetometry dataset. Orthophoto basemap (2022) from Géoportail de la Wallonie. Figure by author.

Results and Discussion

(Ferrous) Metal Artefacts

For the purposes of large-scale geophysical survey, the particular focus here is on larger items of ferrous ordnance (i.e., > 10 cm), which includes grapeshot, cannister shot, solid shot, and howitzer shell fragments (McConnell 1988, pp. 287–332). Such objects are recognized in FM datasets as dipole anomalies (Aspinall et al. 2008b, p. 68) and discrete extreme local outliers in both the QP and IP components of FDEM data (De Smedt et al. 2022). They are less evident in the latter due to lower sensitivity and sampling density. Visible metal anomalies in the FDEM data do, however, show high correspondence with the FM data, confirming that the former is largely redundant for this purpose. Even at the coarser 2 m resolution, some preliminary patterns are visible in the FDEM data in terms of differing concentrations of metal objects between survey areas (Figure 32); unsurprisingly the finer 1 m sampling allows for the resolution of more individual discrete anomalies (though still significantly fewer than the FM data). While non-ferrous conductive metals will also be detected in FDEM surveys, the examples expected here (e.g., lead ammunition, copper alloy uniform components) are much smaller than the sample support/spatial sensitivity of the sensor configuration used. Again, the high correspondence between discrete metal anomalies in the FDEM dataset and dipoles in the FM dataset confirm that they relate overwhelmingly to larger ferrous objects. Systematic metal detection surveys undertaken with a range of conventional detectors (using the same EMI principle) provide a means of verifying the anomalies identified in the larger-scale geophysical surveys. Evidently, these instruments are also capable of detecting the small non-ferrous conductive targets that are relevant to the archaeology of the battle and not detectable by the large-area methods that are the focus here.

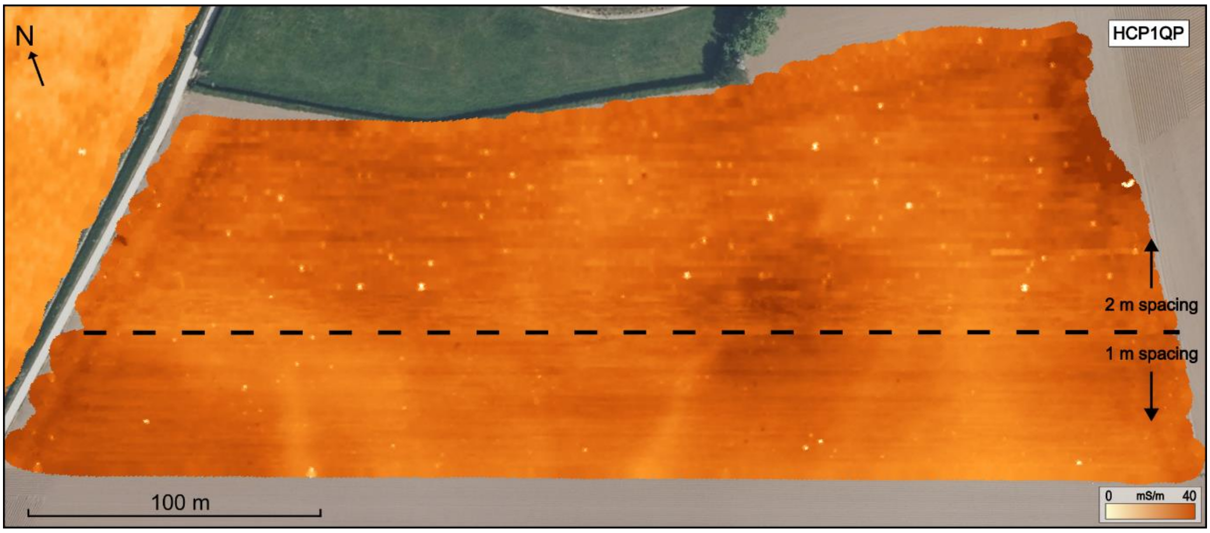

Figure 32: Example of clear differentiation in distribution of metal objects between survey areas (visible as discrete negative (lighter) anomalies) in an FDEM ECa (HCP1QP) dataset. Note how the northern area was surveyed at 2 m interline spacing and the southern area at 1 m but the pattern of more metal in the northern parcel is still apparent. Compare also with magnetometry data for same survey area in Figure 36. Orthophoto basemap (2022) from Géoportail de la Wallonie. Figure by author.

Given the higher sampling density and sensitivity of the FM, the focus here is on extracting probable ferrous metal findspots from these datasets. A semi-automated method is used to identify these features. First, a kernel with a radius of 30 cm is used to compute local minima and maxima for the entire interpolated dataset. Using a threshold of +/- 5 nT, a binary mask is created at the intersection of the minima and maxima. Thus, any cells meeting the minimum or maximum threshold and that are located within 60 cm (2x search radius) of the corresponding value are considered part of a dipole anomaly. The threshold values were derived iteratively and appear suitable across the entire dataset; however, there may also be benefits to using an adaptive filter. After vectorizing the result, a threshold (30 cm) is then used to merge adjacent multi-part features that are likely to derive from the same dipole anomaly. Centroids of each cluster are then extracted to indicate the approximate location of the anomaly.

One limitation is that some of the dipole anomalies may relate to other discrete magnetic objects such as bricks (Aspinall et al. 2008b, p. 69), though the majority are likely ferrous objects. Evidently, not all of these will relate to the battle, with many likely post-dating it and deriving from more modern activities (e.g., agricultural machinery). Nevertheless, the suggestion is that the general spread of material may relate to intensity of combat in particular areas and thus provide high-level insight into potential areas of further exploration.

A comparison of two survey areas effectively demonstrates this premise. The first is at the north end of the battlefield, located on a reverse slope near the farm of Mont Saint-Jean (MSJ) where Anglo-Allied troops were located (a position intensively targeted by French artillery) (Figure 33). The second is at the south end, on the outskirts of the village of Plancenoit, which French and Prussian troops fought for control over (Figure 34). The datasets show a significantly higher concentration of dipole anomalies at the MSJ survey area, which is supported by results from the metal detector survey. Furthermore, the same patterns persist when looking specifically at distributions of lead musket balls recovered from the metal detector surveys. This suggests that ferrous findspots from magnetometry surveys (some of which are fragments of iron projectiles related to the battle) may be an effective proxy for the concentration of musket balls (and thus infantry combat), at least at the field or parcel scale. This premise is also logical from the standpoint of military strategy, given the close association and mutual support between infantry and artillery units in the Napoleonic era (Muir 2000, p. 34).

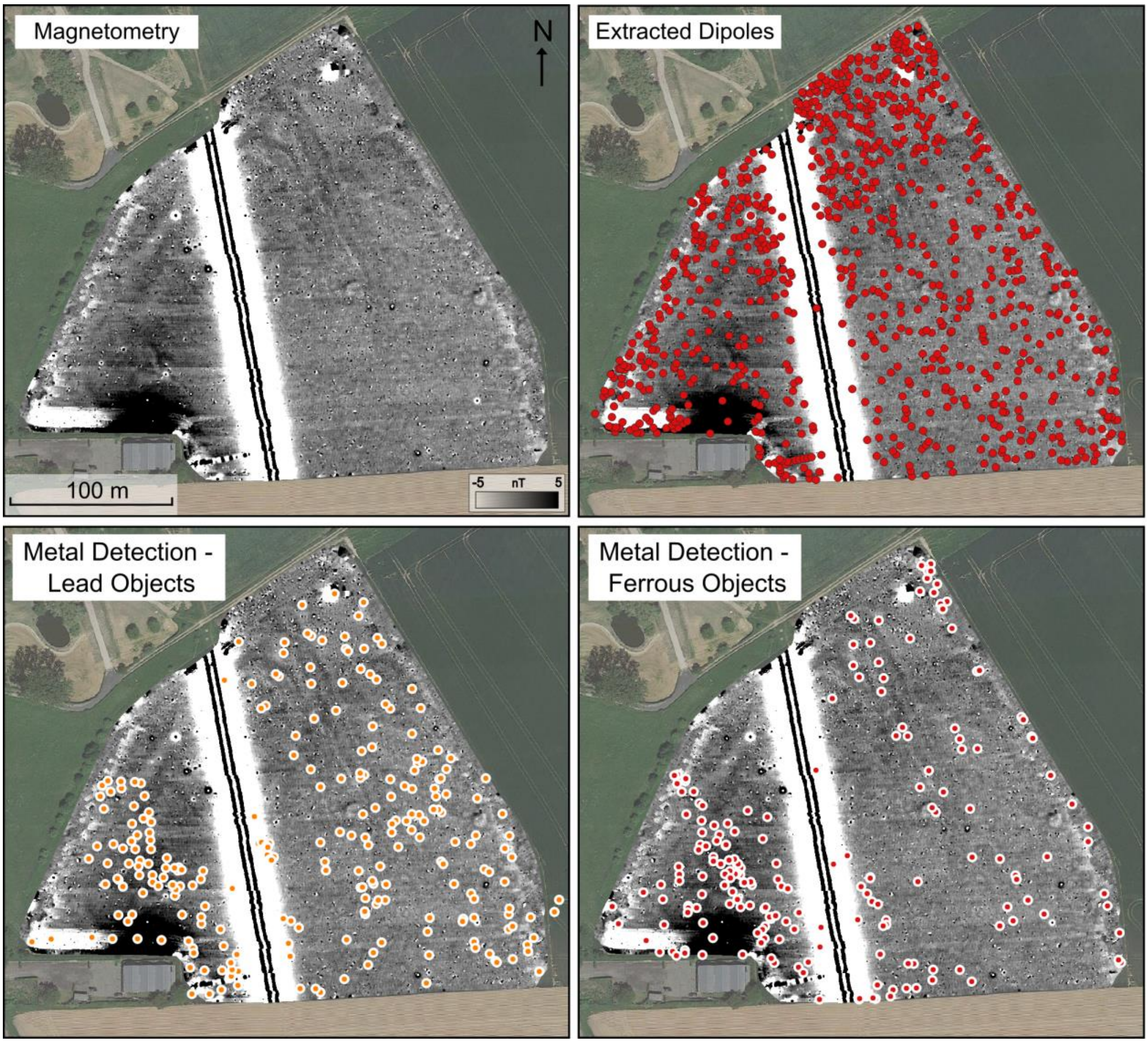

Figure 33: Parcel on the Anglo-Allied reverse slope showing dense concentration of metal objects. Compare with Figure 34. Basemap from Google, 2021. Figure by author.

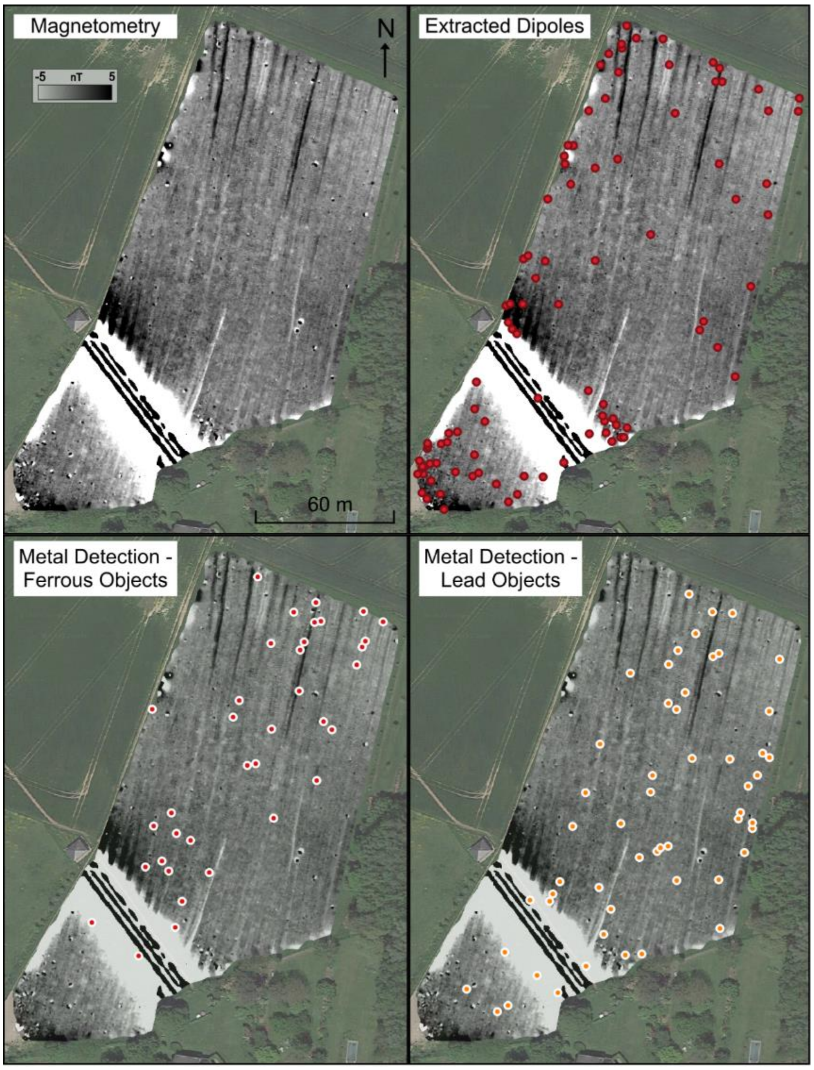

Figure 34: Survey area on the outskirts of the village of Plancenoit, showing relatively sparse concentration of metal objects. Compare with Figure 33. Basemap from Google, 2021. Figure by author.

For the Plancenoit parcel, metal detection was undertaken immediately after the other geophysical surveys. This was not possible for most of the other parcels, which complicates direct comparison of the datasets but also allows for an examination of other possible factors impacting the spread of material in the near-surface. Illicit metal detection (which continues at the site despite legislative protection) and intensive ploughing are two factors which likely have an important impact on the presence of material. Two adjacent parcels at MSJ appear to show this impact (Figure 35). In one, mentioned above, metal detection was undertaken three years prior to the geophysical surveys, though both datasets show similarly dense concentrations. In the adjacent parcel, metal detection was undertaken immediately before geophysical survey with no intermediate ploughing. This yielded a dense concentration of material, similar to the adjacent parcel. Unsurprisingly, the FM dataset is significantly sparser. Given the similarity in the distributions of material in the metal detection datasets from these two fields, however, it seems likely that an episode of (deep) ploughing could cause additional material to be brought up to the near-surface, allowing for its detection in future surveys (as seems to be the case for the adjacent field).

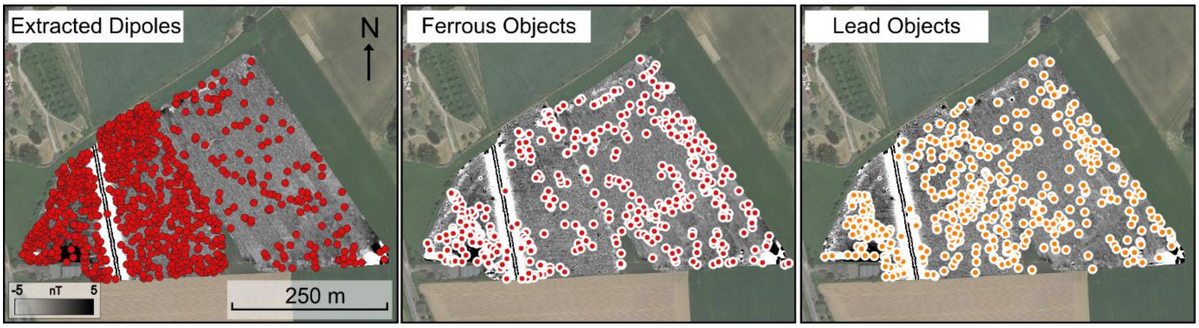

Figure 35: Adjacent survey areas on the reverse slope near MSJ. The left parcel is the one shown in Figure 33. The metal detection results (centre and right panel) show fairly uniform dense concentrations of metal objects

across the two parcels. The right parcel shows significantly fewer dipoles compared to the left in the magnetometry dataset, as it had been recently metal detected. The left parcel was metal detected three years prior to the magnetometry survey. Basemap from Google, 2021. Figure by author.

Finally, two parcels near the Lion Mound monument, immediately in front of the Anglo-Allied position appear to show another effect (Figure 36). One parcel was surveyed in the autumn of 2021 and the other in the autumn of 2022. A comparison of the dipole anomalies in the two parcels shows a remarkable increase in the northern parcel. A possible explanation is the application of a product containing extraneous metal debris such as green waste, as has been thoroughly documented in a range of British case studies (Gerrard et al. 2015; Ainslie 2022). Such a phenomenon has not been observed in a Belgian context, however, and subsequent limited metal detection and examination of the surface did not reveal a notable presence of modern debris. A small overlapping area between the two parcels evocatively demonstrates the increase in dipolar anomalies over the course of one year. Modern landuse is the only explanation for this, with one hypothesis being that an episode of deep ploughing in the northern parcel has resulted in the redistribution of deeper material, rather than the introduction of extraneous material.

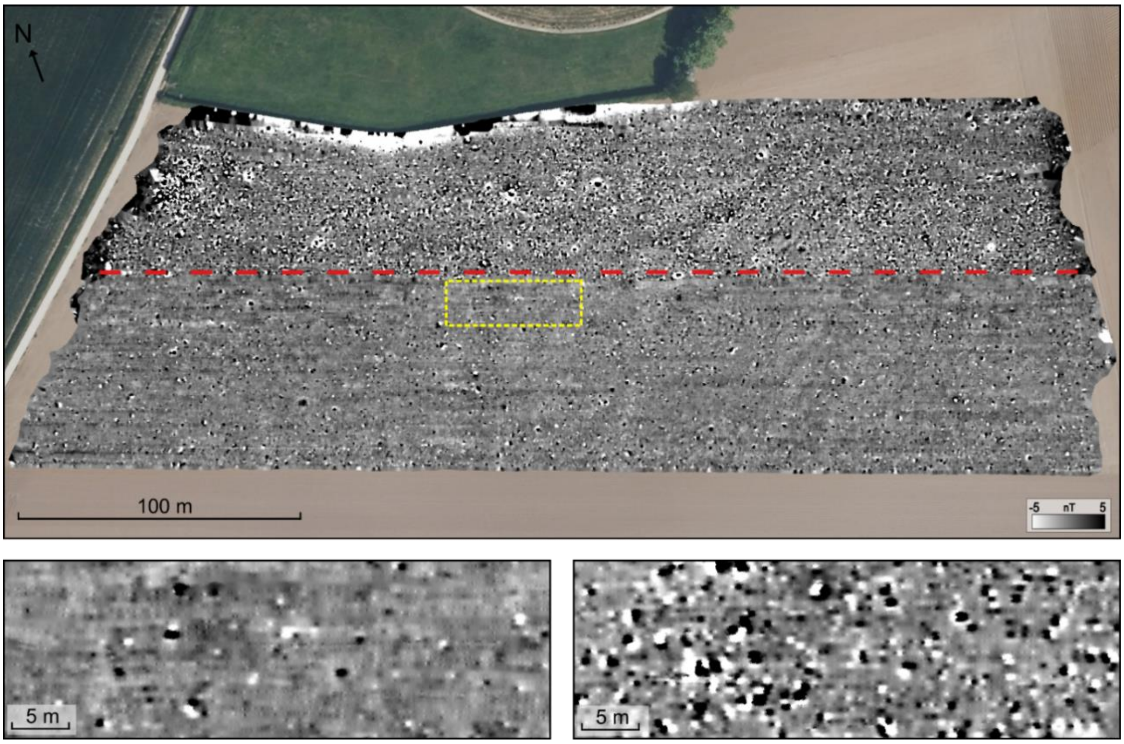

Figure 36: Parcel near the Lion Mound showing significant differences between two survey periods (autumn 2021 and autumn 2022) in terms of dipole anomalies. At top, the dashed red line shows the boundary between the two surveys. The insets at bottom (left 2021 and right 2022) show a detail of the overlapping portion of the surveys (shown in yellow at top). Orthophoto basemap (2022) from Géoportail de la Wallonie. Figure by author.

These examples demonstrate how large-scale geophysical surveys offer a useful qualitative perspective into the distribution of near-surface metal debris in battlefield contexts. Close correlations between these surveys and metal detection datasets suggest the results can be used to gain rapid insight into the intensity of combat across the landscape, with the caveat that more modern intrusive debris is also present as noise. Nevertheless, this noise does not appear to fully remove the validity of the observed patterns, as demonstrated by an examination of objects directly related to the battle (musket balls) from metal detection data sets. Furthermore, additional insight into modern impacts can be gained by examining the different distributions of metal debris between parcels and through time if repeated surveys are undertaken.

Burials

Given the very limited archaeological evidence of human remains at Waterloo and the intriguing questions around the disposal of the dead and their subsequent exhumation (Pollard 2021; Wilkin et al. 2023), burials were an important target of the geophysical surveys. It was not possible to conclusively identify any burial features in the geophysical data from the limited invasive sampling undertaken as part of this work. Possible reasons for this are considered below.

To date, only two burial features have been documented in professional archaeological excavations at the battlefield. One is an isolated burial of a single soldier found at the rear of the Anglo-Allied defensive front. The burial appears to have been rapid, perhaps even without human intervention (e.g., covered with debris after an explosion), with no evidence of an associated negative pit feature (Bosquet et al. 2014, 2015). The other more substantial feature is located a few hundred metres further south and consists of a very shallowly buried (~10 cm beneath the current surface) collection of ammunition boxes, amputated limbs, a complete human skeleton, and several horse skeletons (Bosquet et al. 2023). This appears to represent an episode of battlefield clearance, in which remains were discarded into a nearby ditch at the edge of an existing road and rapidly buried. For the first feature, it was not possible to undertake geophysical survey but it is highly unlikely that any contrast directly related to the burial would have been present, given the lack of an associated pit feature. For the second feature, It was possible to undertake limited magnetometer survey, but noise associated with the adjacent gravel road/path and concentrations of metallic debris mask any more subtle features. Again, the lack of any kind of substantial surviving negative cut feature or contrasting fill likely precludes the geophysical discrimination of this feature.

Of the tens of thousands of dead, only a handful of other remains are accounted for, deriving from accidental discoveries by avocational metal detectorists and construction works (Abbott 2023). Contemporary written and pictorial evidence points to disposal of the dead in burials ranging from single inhumations to mass graves containing dozens, hundreds or thousands of bodies, as well as burning in substantial cremation pyres (Pollard 2021). Setting aside likely artistic license and quantitative hyperbole, it is clear that the cleanup of the battlefield and disposal of the dead would have left substantial physical evidence on the battlefield, some of which would be expected to yield geophysical contrasts if adequately preserved.

The most likely candidates for geophysical survey are the larger mass graves and cremation features, which should be expected to yield magnetic contrasts associated with local changes in induced magnetism from the disruption of natural soil susceptibility or possibly thermoremanent magnetism in the case of burning. Electrical contrasts due to textural differences resulting from soil perturbation might also be expected in certain areas where the sandy Tertiary substrate is less deeply buried beneath the Quaternary loess cover. Notwithstanding some potential targets for which it has not yet been possible to sample invasively, these features have thus far not appeared in the geophysical dataset, which covers approximately 10% of the battlefield. Given the sheer number of casualties and reported extent of burial features, this is noteworthy. It should be noted, however, that geophysical survey has not yet been possible in many of the areas with highest potential for burial features based on the documentary evidence (Pollard 2021, fig. 16).

One explanation for this apparent absence is the strong possibility of removal of many of the bodies from the battlefield, for which concrete historical evidence has recently come to light (Wilkin et al. 2023). This relates to the use of bone in two industrial processes: manufacture of bonemeal for fertilizer and bone char for refining of sugar. There is direct historical evidence for the occurrence of the latter at Waterloo in the form of contemporary documentation, supported by the location of a beet refining factory in the immediate vicinity. For the former, the evidence is more circumstantial as it relates to accounts for other battlefields and more generally to the known existence of the practice at a large scale in the 19th century (ibid). In either case, it seems a certainty that removal of bodies from mass graves took place at an appreciable scale. Afterwards, it is likely that the empty pits would be ploughed up and the land converted back to agricultural use, thus homogenizing the soil profile and removing any geophysical contrast relating to the feature. Indeed, there is concrete historical evidence for the rapid return of agriculture to the landscape (Pollard 2021, p. 83). There is also documentary evidence that farmers avoided (or were instructed to avoid) burial features in their return to agricultural operations (Bosquet and Moulaert 2017). This may suggest that if or when these features were emptied, they would have been subsequently ploughed up. In the case of cremation pyres, it is less likely that the geophysical signature would be erased by ploughing, as a general ferrimagnetic (or perhaps thermoremanent) enhancement should still be present. While some concentrations of burnt material were encountered in the surveys (discussed further below), their small extent makes it unlikely that they relate to the burning of bodies.

There is also a variety of evidence to suggest that many of the burial features were quite superficial. This reduces the likelihood of a strong geophysical contrast, particularly if the depth of the features did not greatly exceed that of the ploughzone. Accounts from visitors to the battlefield in the aftermath note that many graves were extremely shallow, with remains visibly protruding above the ground in some cases (Pollard 2021). There is also archaeological evidence of very superficial burial, in both examples noted above. In fact, in the case of the isolated burial, plough damage was visible, despite its relatively greater depth, and more extensive damage seems to have been avoided only because of a more recent overlying colluvial deposit. Similarly, anecdotal evidence from accidental discoveries of remains by metal detectorists indicates that they were found in the current ploughzone, within the limited depth range of conventional metal detectors, and perhaps in a secondary context (Abbott 2023). The shallow depth of the original burial features thus makes it even more likely that they would be erased by ploughing, particularly as ploughing depth has increased substantially with the introduction of mechanized agriculture (Van Oost et al. 2000).

While these suggestions remain somewhat unsatisfying, they may explain the apparent lack of obvious evidence for burial or cremation features in the (albeit incomplete) geophysical dataset from Waterloo. Examples from elsewhere on the site (discussed further below) demonstrate that thermoremanent features and substantial pit excavations generate clear and recognizable geophysical contrasts in the soil environment. As of yet, however, none of these have been directly linked to features relating to the disposal of the dead. If such a feature is identified at Waterloo or in a comparable soil environment, sampling and *in situ* recording of geophysical properties would allow for a more reliable forward model of the expected contrast and perhaps a more robust analysis and interpretation of the dataset.

Field Fortifications

While there is some suggestion that Wellington's forces intended to construct field fortifications at Waterloo associated with their artillery positions (Muir 2000, p. 20), there is no concrete historical evidence that they actually did so. Thus, it is not surprising that there appears to be an absence of purpose-built defensive features present in the dataset. Instead, pre-existing elements of the natural and anthropogenic landscape were incorporated into the battle for strategic purposes (see below).

Encampments

Some of the surveyed areas are known to be in locations where soldiers were encamped on the night before the battle. Recent preventive excavations immediately outside the protected battlefield area uncovered several features interpreted as being related to an Anglo-Allied encampment in an area where troops from the Duchy of Brunswick were stationed before and during the battle (Danese 2020). These consisted of ephemeral pit features, one of which contained remains of a hearth, and are comparable to those widely reported from other military encampment sites (Poulain et al. 2022). They were noted as being extremely shallow (the deepest being 30 cm), extending barely beyond the topsoil layer and degraded by erosion. Similar features were encountered at another preventative excavation nearby in Wavre (Moulaert, Sosnowska, et al. 2020), where a battle was fought on the same day (see Figure 1). Notably, in contrast to the Waterloo features noted above which were in pastureland, these were found in a cultivated field but extended only very slightly into the subsoil. Nevertheless, this indicates that survival of these features is possible (if perhaps less likely) in ploughed areas.

Definitive evidence for similar pit features and hearths has not yet been found in the geophysical dataset from Waterloo (or in any of the previous excavations conducted by Waterloo Uncovered). Despite significant rainfall on the night of the battle and some reports of difficulty maintaining fires (Muir 2013, p. 55), there are numerous historical accounts of fires being lit in the Allied bivouacs (Adkin 2001, pp. 33, 141, 155). The saturated ground conditions frequently mentioned in eyewitness accounts (Adkin 2001, p. 33) may partly explain the lack of dug-out shelter and cooking structures that often characterize other battlefields.[15] Archaeological evidence from immediately outside the study area, however, does confirm that some form of shallowly dug features did exist. It should, therefore, be assumed that similar features would have been present in some of the surveyed areas, particularly those located in proximity to the reverse slope where the majority of Wellington's forces were encamped (Adkin 2001, p. 156). It is thus necessary again to consider factors which might explain the lack of visibility of such features in the geophysical dataset.

[15] Saturated ground conditions were encountered at an early 19th-century French camp (though in the context of a training and garrison camp, rather than battlefield) on the Belgian coast at Ostend and are noted as being the reason for the lack of dugout structures (Lemaire 2022, fig. 4.13).

First, the dimensions of the features could be a limiting factor. In the case of the hearths, those recorded at Waterloo and Wavre are noted as having dimensions of 0.5 m or smaller (Danese 2020; Moulaert, Sosnowska, et al. 2020). In some cases, more substantial communal hearths have also been documented at other sites (Authom and Denis 2022; Authom et al. 2022). For the more typical smaller features, however, there is a chance that the 0.5 m cross-line sampling resolution used here would have been insufficient to reliably capture any resulting anomalies. On the other hand, the larger associated pit features, most of which seem to have dimensions of 1 m or more per side are of a more suitable size. Given their shallow nature and the fact that those documented in archaeological contexts seem to rarely surpass the uppermost soil horizon (topsoil/ploughzone), however, it is unlikely that a significant geophysical contrast would be present. Furthermore, they were likely rapidly infilled with a similar homogenous material. Indeed, in the Waterloo example noted above, it was remarked that discriminating their boundaries during excavation was particularly challenging (Danese 2020). Lastly, these ephemeral features also face the same challenges associated with destruction through erosion and intensive ploughing noted above in the case of burials. Despite their documentation in cultivated fields as noted in the Wavre case above, their survival in arable land seems less likely than in forested or pastureland (which make up only a small portion of the landscape at Waterloo).

Certain magnetic anomalies identified during geophysical surveys at Waterloo have been shown to relate to concentrations of burnt material but cannot be definitively tied to a military occupation at present. In some cases, associated structural material such as brick and mortar strongly suggests that they are not associated with military activity but instead other forms of domestic occupation (Figure 37A). Other examples relate to concentrations of waste fuel material (clinker, coal, etc), some of which are very superficial and likely recent (Figure 37C) while others are more deeply buried (Figure 37B). These ephemeral scatters do not seem to be related to pit features or obvious *in situ* heating and thus may be discarded material in secondary contexts.

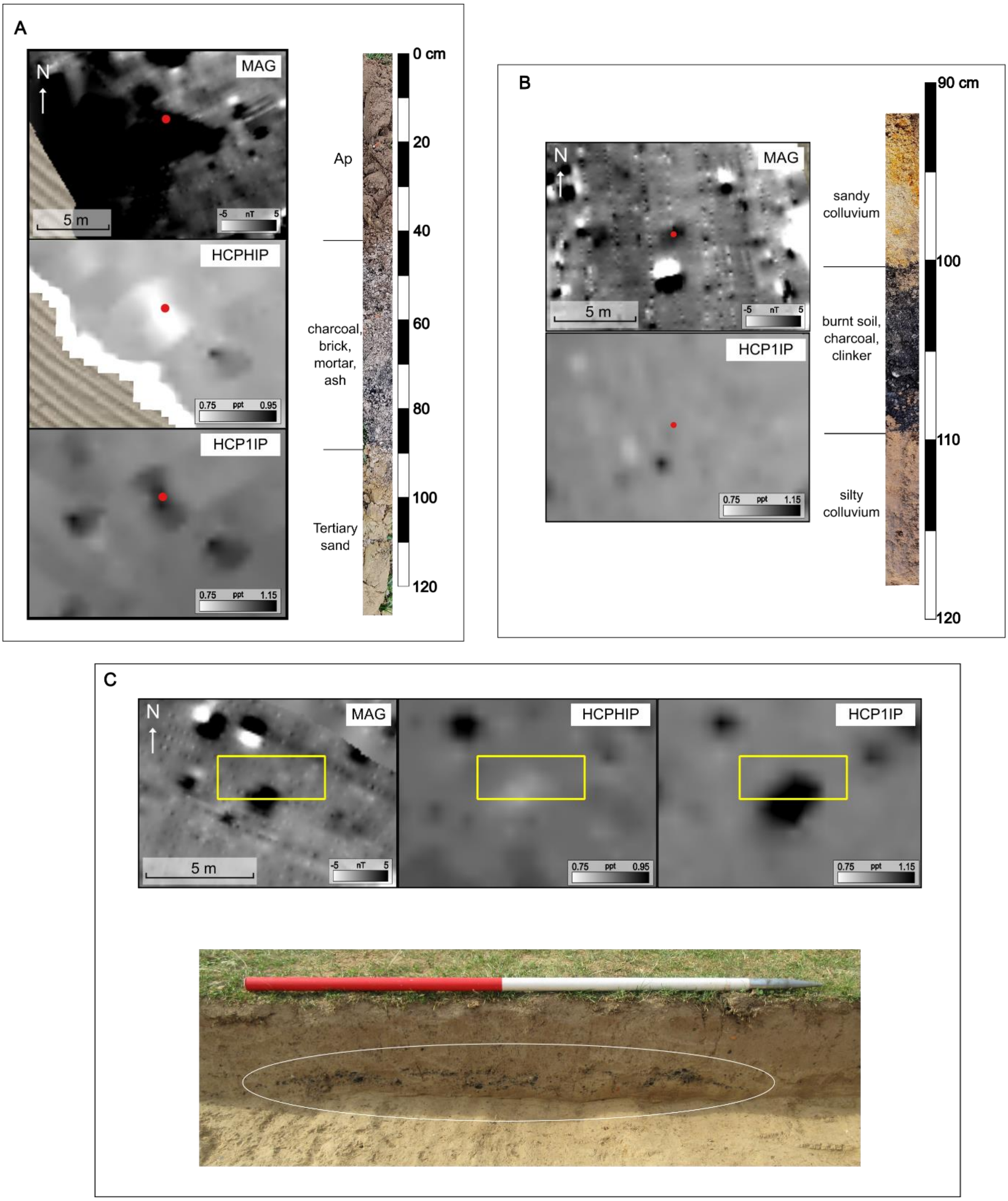

Figure 37: Examples of different discrete magnetic anomalies. A: Deposit of charcoal and ash with brick/mortar inclusions south of Hougoumont. The sign change from the 0.5 to 1m coil pair indicated that the feature would be between 0.3 and 0.6 m below the sensor, confirmed in the borehole (immediately beneath the ploughzone at 0.4 m). B: Deep lens of burnt soil/slag/clinker near La Belle Alliance. The feature is very small and located between two FDEM survey lines, thus not rendering a response in this dataset. Detail of borehole showing magnetic layer at 100+ cm beneath colluvial deposits (mixed sandy lens above and siltier below). C: Superficial lens of burnt waste material in test excavation. Note the sign change in the shallowest FDEM coil pairs, as well as the smaller area of the feature in the magnetometry data. Figures and photos by author.

One intriguing feature was revealed to be a pit beneath the current ploughzone, containing a dense accumulation of charcoal and dug into the subsoil (Figure 38). Its location on the reverse slope at the heart of the Anglo-Allied position offers the intriguing possibility that it may relate to some activity associated with the battle. Ultimately, however, it is very difficult to determine the true nature of these features from borehole sampling.

In one instance, a hearth feature relating to recent military reenactors was encountered during test excavations (Waterloo Uncovered 2015a), which was linked to a magnetic anomaly from FDEM surveys (Figure 39). The discovery of this feature was encouraging, as it suggests that analogous examples dating to the battle itself could be recognized, if suitably preserved. Other superficial scatters of burnt material noted above from near Plancenoit may relate to similar episodes, as the current landowner noted that reenactors also bivouacked in the immediate area.

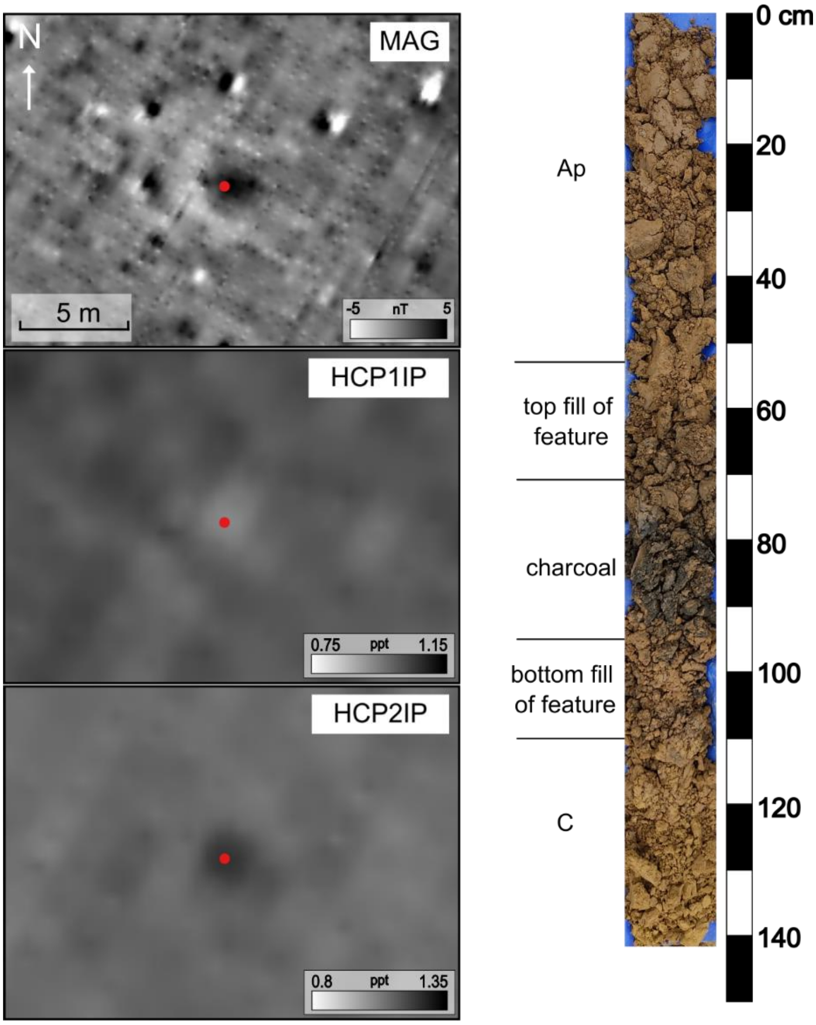

Figure 38: Magnetic anomaly on the Anglo-Allied reverse slope. The sign change from the 1 to 2 m coil pair indicated the feature was relatively deep (between 0.6 and 1.2 m). This was confirmed by a borehole which revealed a concentration of organic material and charcoal. Figures and photo by author.

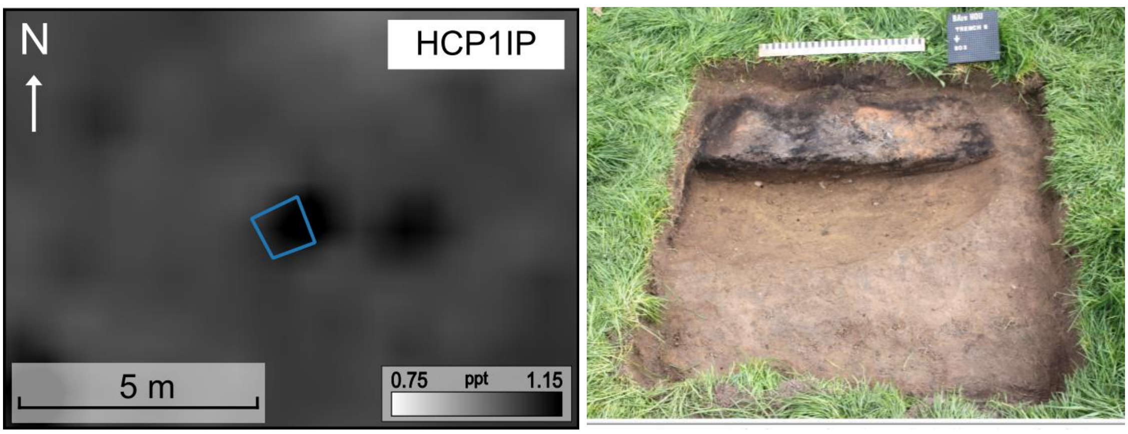

Figure 39: Magnetic anomaly near Hougoumont Farm. The lack of sign change suggested a superficial feature and a test excavation revealed a very recent hearth related to reenactor activities. Figure by author, photo courtesy of Waterloo Uncovered (used with permission).

Another intriguing magnetic feature was found just in front of Wellington's position (near the present-day Lion Mound monument) and revealed in a borehole sample to be a thin lens of charcoal and slag/ferrous nodules beneath approximately 0.7 m of colluvial overburden. Test excavation revealed an annular feature corresponding to the magnetic anomaly and comprised of a thin compact surface of charcoal, slag, and hammer scale interpreted as the remains of a small forge (Figure 40). The feature was revealed to be set in a terraced pit dug into the subsoil and appears to be a working surface (perhaps centred around an anvil). Magnetic susceptibility readings of the surface of the feature were in the range of 10-45 (10^{-3} SI units [msu]), while the immediately adjacent natural surface (Holocene Bt horizon) on the same level was three orders of magnitude lower (ranging from 1-2 x 10^{-5} msu). Samples from the upper fill of the pit feature (averaging 8.7 x 10^{-5} msu) were also approximately 6-7 x more magnetic than the subsoil (averaging 1.3 x 10^{-5} msu, based on lab susceptibility measurements. Meanwhile, there is no electrical contrast, as seen in the ECa data and confirmed by measurements of the feature profile and bulk samples. The origin of the feature is unclear but it may relate to the construction of the Lion Mound monument, built a decade after the battle. Contemporary images (Figure 41) show the construction of the monument with associated infrastructure and it is easy to imagine the presence of a small mobile forge on site for the production and repair of necessary tooling.

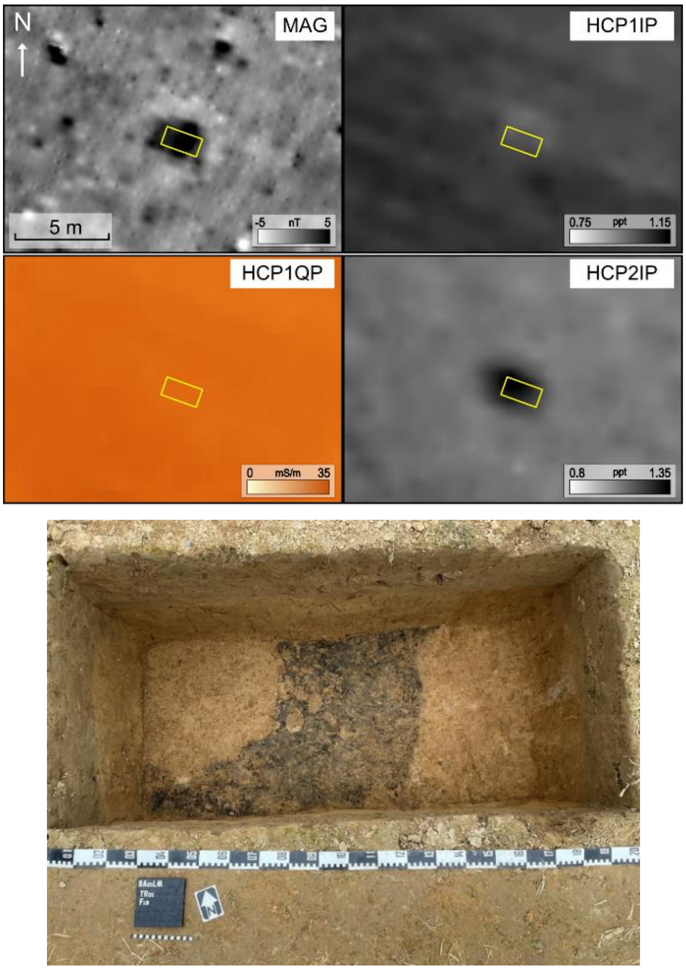

Figure 40: Magnetic anomaly near the Lion Mound. The magnetometer response is moderately strong and the sign change in the IP data from the 1 to 2 m coil pair suggested a relatively deep feature (> ca. 0.5 m), while no contrast was present in the QP response. Test excavations revealed a thin spread of slag, burnt compacted soil, and hammer scale. Figures and photo by author.

Figure 41: Lithograph showing construction of Lion Mound (after Bertrand drawing, from De Cloet (1825), Creative Commons license provided by Ghent University Library). View appears to be looking southwest based on the structure shown at right, visible on near-contemporary historic maps. This would place the excavated area from Figure 40 out of view on the opposite side of the mound.

A GPR survey was also conducted across this feature. Given the compact surface of the feature compared to the surrounding soil matrix, it was considered to be a likely candidate for detection using this method. Two profiles are shown in Figure 42. In the first, the excavation unit appears to be visible as a series of discontinuous reflections between about 2.5 and 4.5 m. The ploughzone can be identified throughout the profile as higher amplitude reflections at about 0.4 m depth. The feature appears to be visible at about 0.8 m depth in the centre of the profile as a series of weak but coherent reflections. Significant attenuation in the lower part of the profile hinders interpretation (with bulk conductivity measured at about 30 mS/m along the excavated profile). There is also significant noise associated with poor ground coupling (the ground surface having been ploughed immediately beforehand). In the second profile, conducted to the south just outside the excavation unit, the ploughzone can also be recognized at the same depth. The feature can be identified in moderately strong reflections at about 0.8 m depth between 3.8 and 5.2 m. A strong reflector is also located at 0.4 m depth (at the ploughzone interface) in the location of the feature.

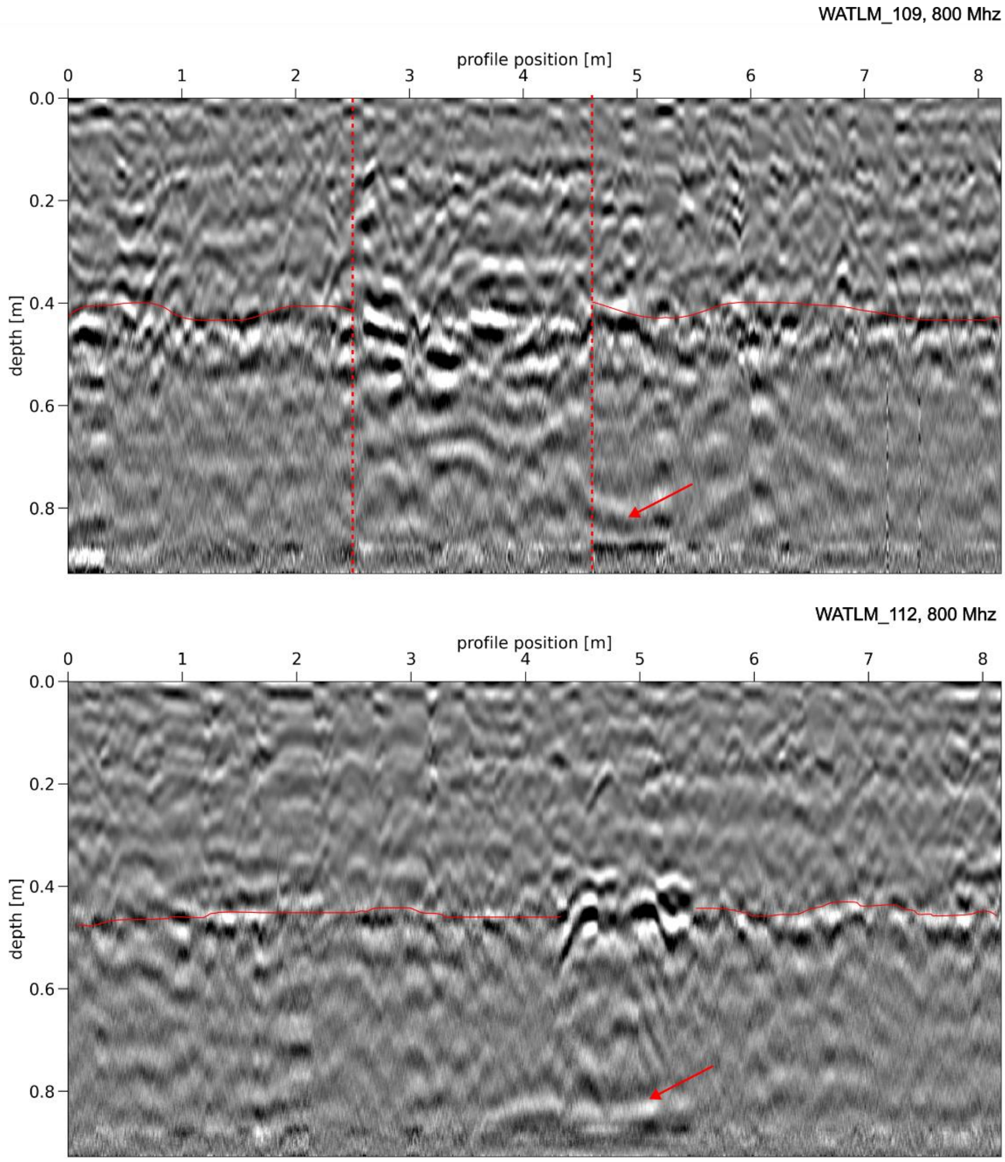

Figure 42: GPR profiles over forge feature. Top profile crosses excavation unit, which is marked by the two dashed lines. The solid lines indicate the bottom of the ploughzone at ca. 40 cm, while the arrows indicate a reflection associated with the forge feature. A large reflection is also visible in the bottom profile, interrupting the ploughzone reflection plane. Figures by author.

Several other anomalies in the same parcel appeared to be good candidates for similar features. They are characterized as moderately positive magnetic anomalies (with a sign change in the FDEM data) with no associated discrete electrical contrasts. Borehole sampling, however, revealed these features to be natural concentrations of iron oxides associated with Tertiary deposits (Figure 43). These sandy outcrops have been encountered in various areas across the site where the loess cover is thin or non-existent. Portions of these units are characterized by gravel-rich deposits containing flint pebbles, sandstones, and iron-rich conglomerates (Laga et al. 2002; Rommens et al. 2007; Mees and Langohr 2020).

Elsewhere, linear anomalies were also encountered that related to similar Tertiary deposits. Rather than discrete outcrops, these seem to represent eroded gullies infilled with similar gravel deposits (Figure 44). While these features can sometimes be recognized by their association with significant changes in electrical properties (relating to textural differences characterizing Tertiary deposits), their interpretation is seldom straightforward on the basis of sensor data alone.

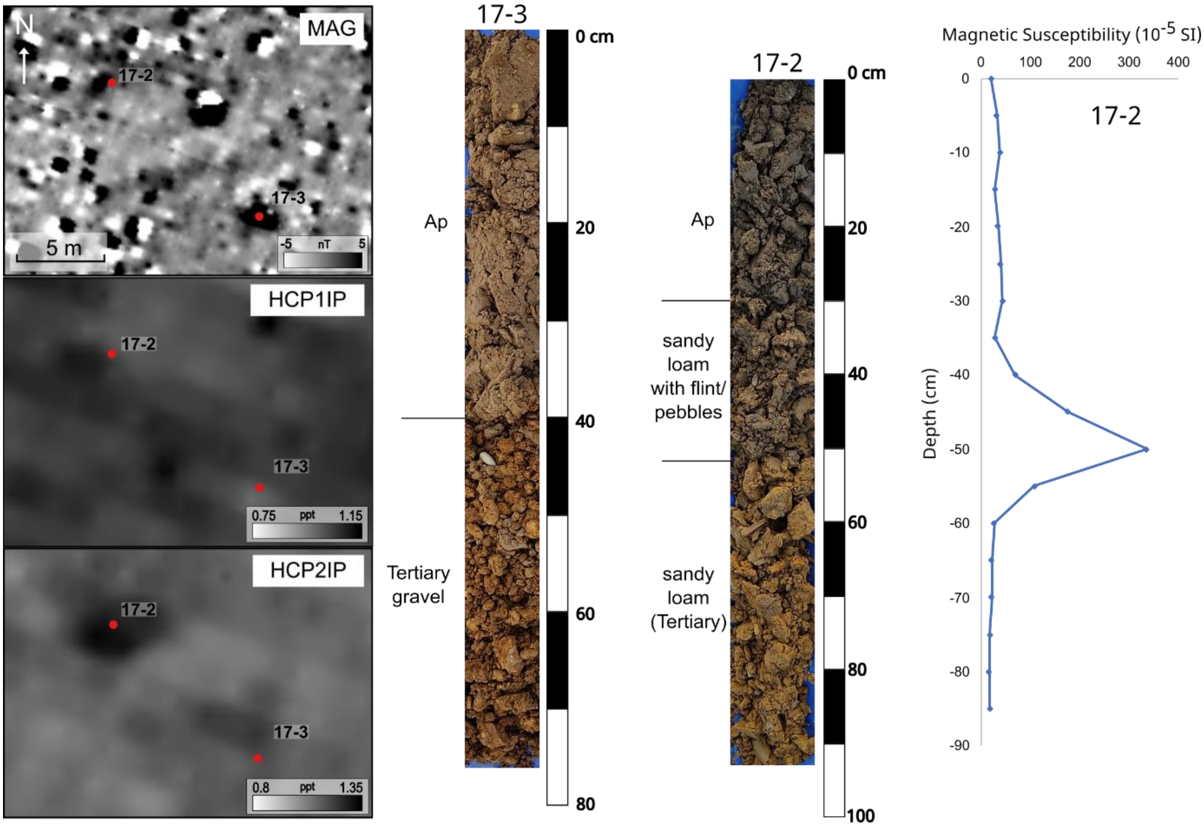

Figure 43: Examples of discrete magnetic features in same parcel as the feature shown in Figure 40, which were revealed to relate to concentrations of iron-rich gravels associated with Tertiary deposits. The magnetic susceptibility log clearly delineates the zone of strong magnetic enhancement. Figures and photos by author.

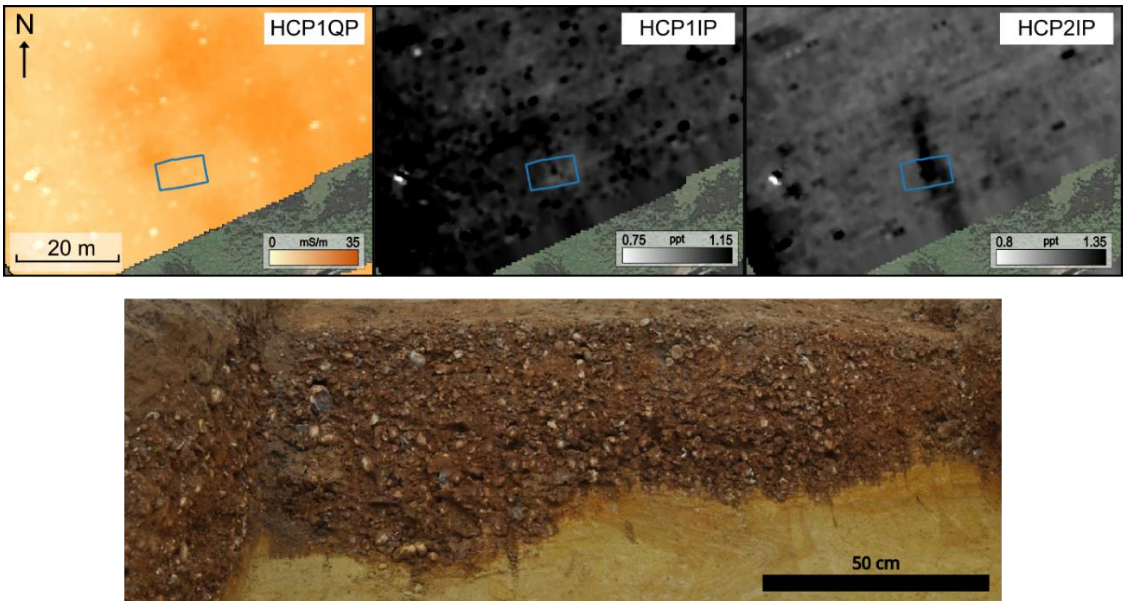

Figure 44: Linear magnetic anomaly near Hougoumont Farm, visible particularly in the deepest coil pair. The electrical contrasts in the broader area suggest an outcrop of Tertiary sand. Test excavations revealed a thick layer of iron-rich pebbles and flints similar to those shown in Figure 43. Figures by author, photo courtesy of Waterloo Uncovered (used with permission).

Another type of natural soil feature was encountered at two survey locations and also linked to strong discrete magnetic anomalies (Figure 45). These features were revealed to be thin but distinct lenses of dark red-purple soil without any associated flint or iron oxide pebble inclusions but do appear in association with sandy Tertiary outcrops. On one occasion, the lens was uncovered at a very shallow depth (0.25 m), while in the other it was considerably deeper (0.9 m). In both cases, the lenses were measured as having approximately 100x the MS of the surrounding matrix. While the exact genesis and mineralogy of these features is unclear, they appear to represent natural soil lenses very rich in ferrimagnetic minerals. In both cases, no other anthropogenic material was found in association.

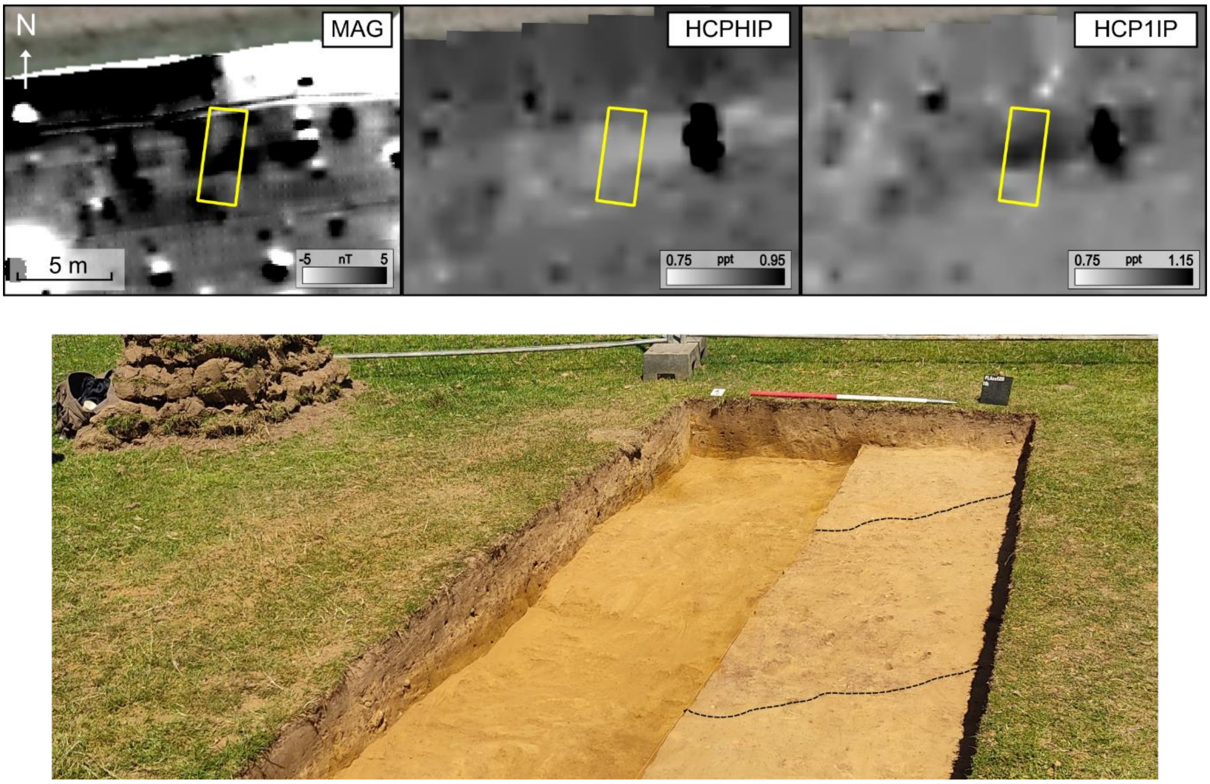

Figure 45: Magnetic anomaly near Plancenoit and results of test trench. Excavation revealed a highly magnetic red-purple lens (outlined in black in plan, already excavated on left half of image) about 0.25 m beneath the surface. Figures and photo by author.

Finally, a discrete magnetic feature near the Belle Alliance inn was revealed to be a tree throw/pit (Figure 48). It is particularly evident in the FM data and more subtly in the FDEM IP data with a sign change between the 1 and 2 m HCP coil pairs. A borehole revealed dense concentrations of wood between 0.6 and 1 m over a Tertiary sand substrate. No anthropogenic material was found in association. Together, these examples illustrate the perils of interpreting all morphologically-similar discrete magnetic anomalies as being anthropogenic in origin, showing that they can also have several different natural causes.

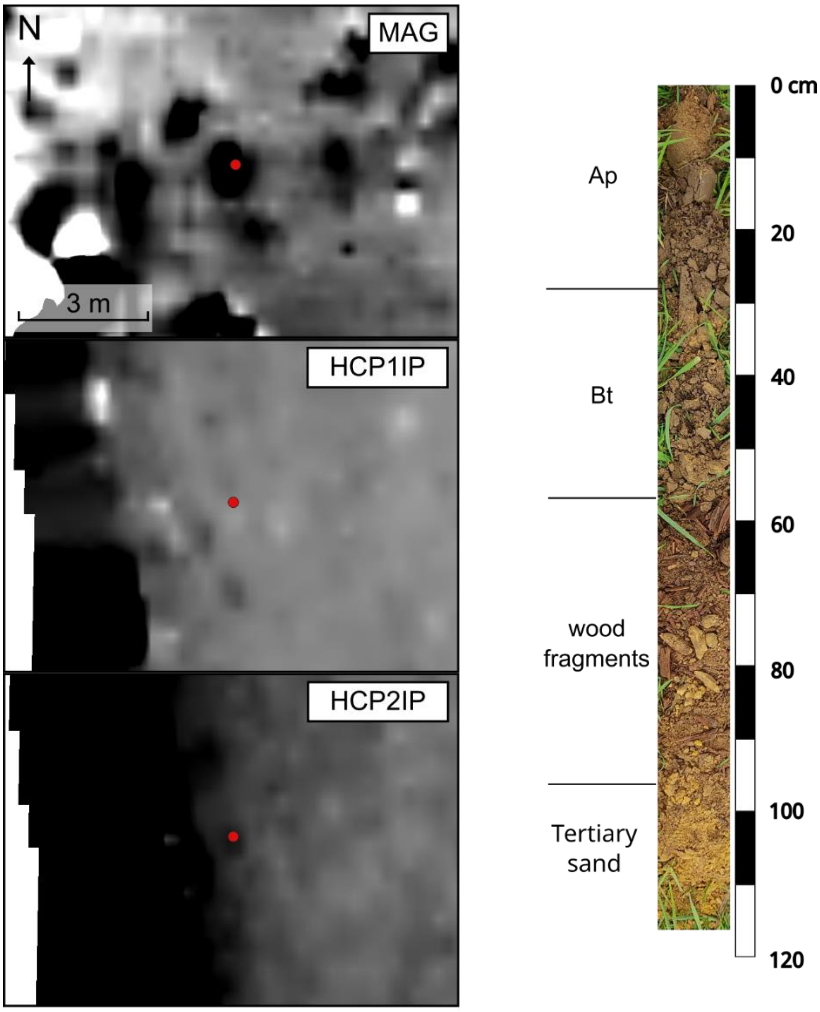

Figure 46: Magnetic anomaly revealed to be a tree throw/pit after borehole sampling. Figures and photo by author.

While the archaeological signatures of typical camp features are now fairly well understood as a result of a recent research focus (Poulain et al. 2022), the associated geophysical signatures are less well understood. In rare instances where geophysical surveys have been completed in advance of excavation of campsites, negative results have been reported (Brion 2022, p. 77). As discussed above for burial features, however, it will be necessary to carefully document the geophysical properties of these features during archaeological excavation to better forward model their contrasts and determine if and how they can best be recognized in prospection datasets.

Anthropogenic Terrain

This broad category refers to the diverse landscape elements that are the product of human action and not captured by the above discussion. More specifically, it refers to features that were not created as direct results of conflict action but may have played a role during the battle or altered the landscape in the aftermath.

These elements are known to have played a key role in the selection of the site of the battle. Complementing the natural defensibility offered by the low ridge and reverse slope where Wellington positioned his army, a series of associated farm buildings were used as forward bastions to defend the position (Muir 2013, p. 58). The role of these prominent features and the fierce fighting that occurred for possession of them is well documented in the historical record. The village of Plancenoit played a similar role in the combat between the French and Prussians, with the church in the centre of the village being a particular focal point (Adkin 2001, p. 128).

Remains of a hitherto unknown brick structure were revealed in surveys on the outskirts of Plancenoit. The eastern and southern portions of a rectilinear anomaly are well defined in the FM data, terminating at more pronounced anomalies that may be piers (Figure 47). A series of less distinct linear anomalies are also present further west and may be part of the same structure or an adjacent one. The feature is only faintly visible in the FDEM IP component, but a sign change from the HCP1 to HCP2 coil pairs indicate that it is relatively deep. A test excavation bisecting the eastern wall revealed a brick rubble filled trench without any *in situ* foundations, indicating it may have been largely robbed out. A coin dating to 1894 atop this destruction horizon provides a *terminus post quem* for the destruction of the feature. While the structure is not depicted on any contemporary historical maps, there is a possibility that it existed at the time of the battle, perhaps as an outbuilding associated with one of the nearby farms. If so, it may have played a role in the skirmishing that took place in the area.

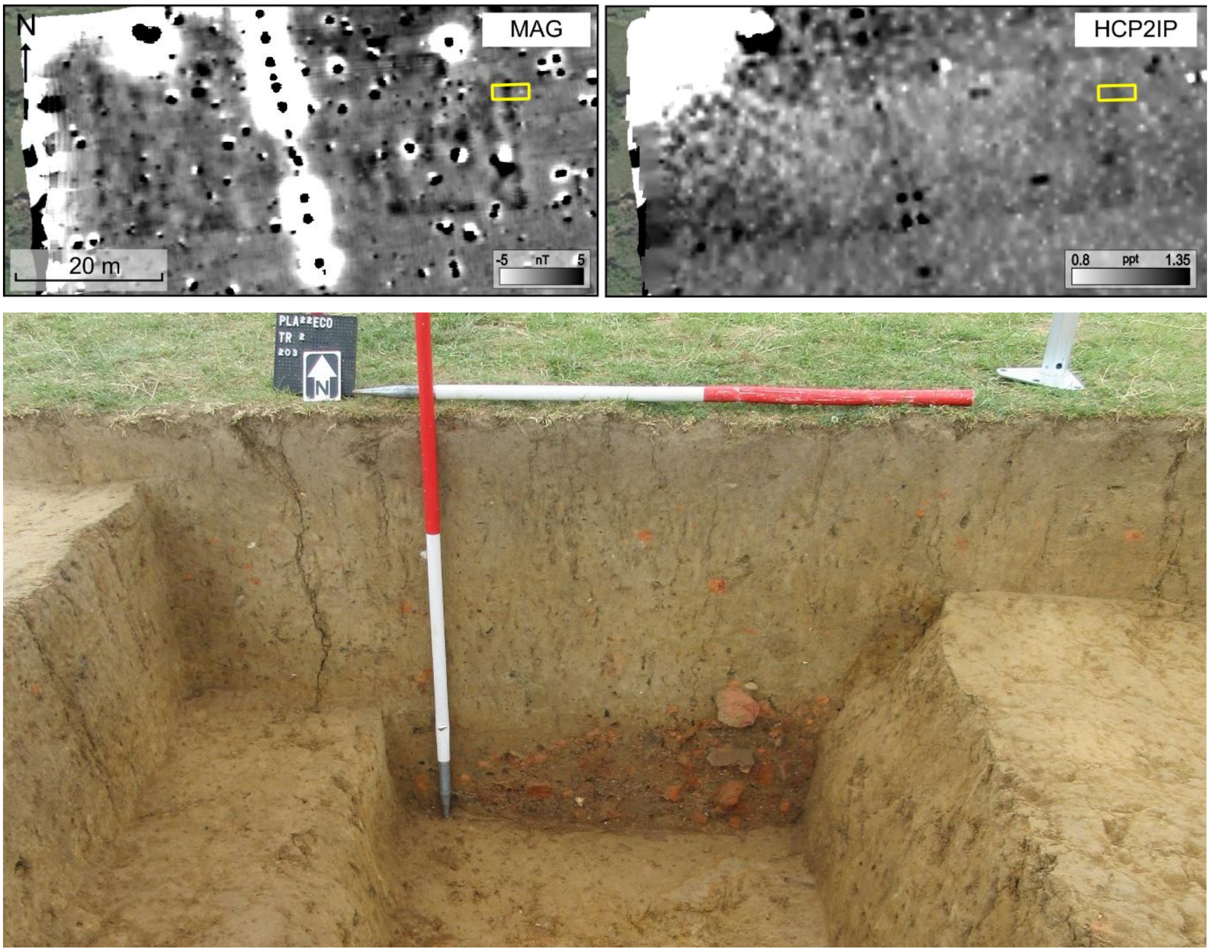

Figure 47: Rectilinear feature revealed to be remains of brick structure on outskirts of village of Plancenoit. Figures by author, photo courtesy of Waterloo Uncovered (used with permission).

At the farm of Hougoumont on the Anglo-Allied right flank, another sizeable magnetic feature was revealed (Figure 48). The shape of this feature is less distinct (sub-rectangular, measuring 4x5 m) but its position correlates very well with a small chapel shown on the 1777 Ferraris map, supporting previous findings of the exceptionally high quality of these maps (Vervust 2016). Borehole sampling confirmed the presence of a dense brick deposit and test excavations revealed the presence of *in situ* foundations. The Ferraris map provides a *terminus post quem* for the feature, but it is unclear if it existed at the time of the battle and there are no known contemporary historical references to it. If still present, however, it is reasonable to assume that it would have played an active part in the heavy fighting that took place in the wood as the French forces attempted to take Hougoumont. As with the forge feature near the Lion Mound, a small GPR survey was undertaken over the chapel feature. This survey was largely inconclusive, however, with significant noise in the upper portion of the profile which is likely related to signal scattering from the abundant rubble in the ploughzone. Again, attenuation is significant, and conductivity measurements on a nearby profile averaged approximately 40 mS/m.

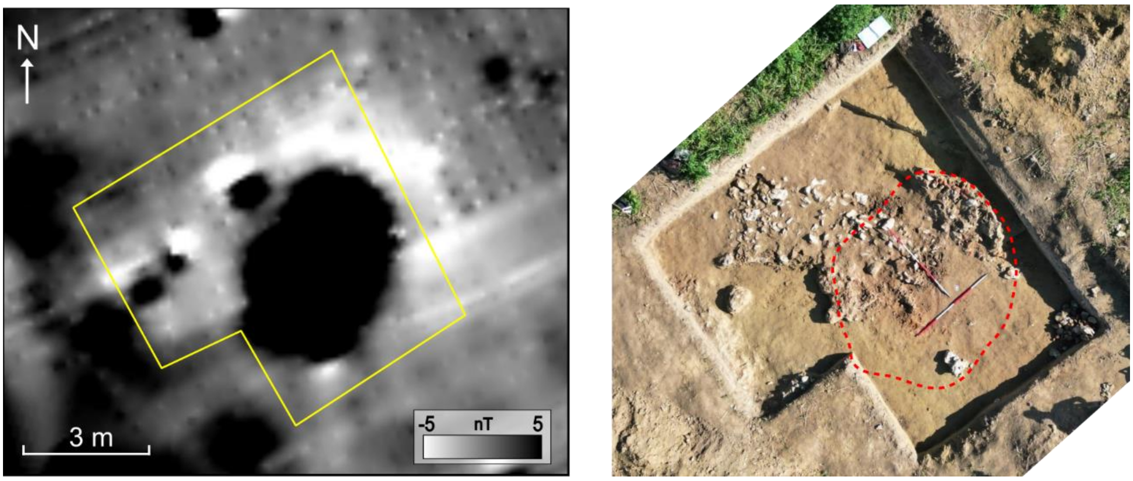

Figure 48: Magnetic feature found to south of Hougoumont farm, revealed to be remains of brick structure. The concentration of brick seen in the eastern part of the trench correlates very well with the distinct positive magnetic anomaly (anomaly footprint outlined in red on excavation photo). Figure by author, photo courtesy of Waterloo Uncovered (used with permission).

Another intriguing feature was revealed a mere 50 m to the east of the chapel (Figure 49). A distinct conductive zone measuring approximately 30 x 50 m is visible in the FDEM data, which is particularly evident in the deeper coil pairs where the influence of metal objects is lesser. A corresponding area of enhanced MSa is present in the IP component of the FDEM data. This is again especially pronounced in the HCP2 coil pair, indicating that the feature is relatively deep. By contrast, the FM data does not show any evident zone of enhanced susceptibility, which is perhaps a result of the inherent high-pass filter effect of the gradiometer configuration. There is, however, a very distinct concentration of dipole anomalies that corresponds to the high ECa and MSa zones noted above. Interestingly, prior metal detection (from 2015) revealed only a few ferrous objects in the area, suggesting that most of the recorded anomalies are quite deep (or relate to other objects such as bricks).

Test excavations bisecting the feature revealed a substantial pit feature filled with a mix of anthropogenic and colluvial deposits to a maximum depth of over 2 m. A cadastral map from an 1816 bill of sale labels the adjacent parcel as *La prairie à la briquetterie*. The discovery of a brick kiln some 200 m to the northwest (also identified in the magnetic datasets) further hints at the function of the feature as an extraction pit. Evidence for the removal of the clay-rich Bt horizon, with the fill directly overlying the Tertiary sands, provides further support. At the base of the feature, several objects relating to the battle were found *in situ*, including musket balls and a gunflint, indicating that the pit was at least partially open at the time of the battle. It is logical to assume that such a substantial feature would have played a role in the fierce fighting around Hougoumont, particularly as a means of cover and concealment (Babits 2014). Similarly, it could have been a convenient place to dispose of debris, or indeed human remains, when undertaking battlefield cleanup, although this has not been documented by the test excavations to date (which have explored about 10% of the total area of the feature).

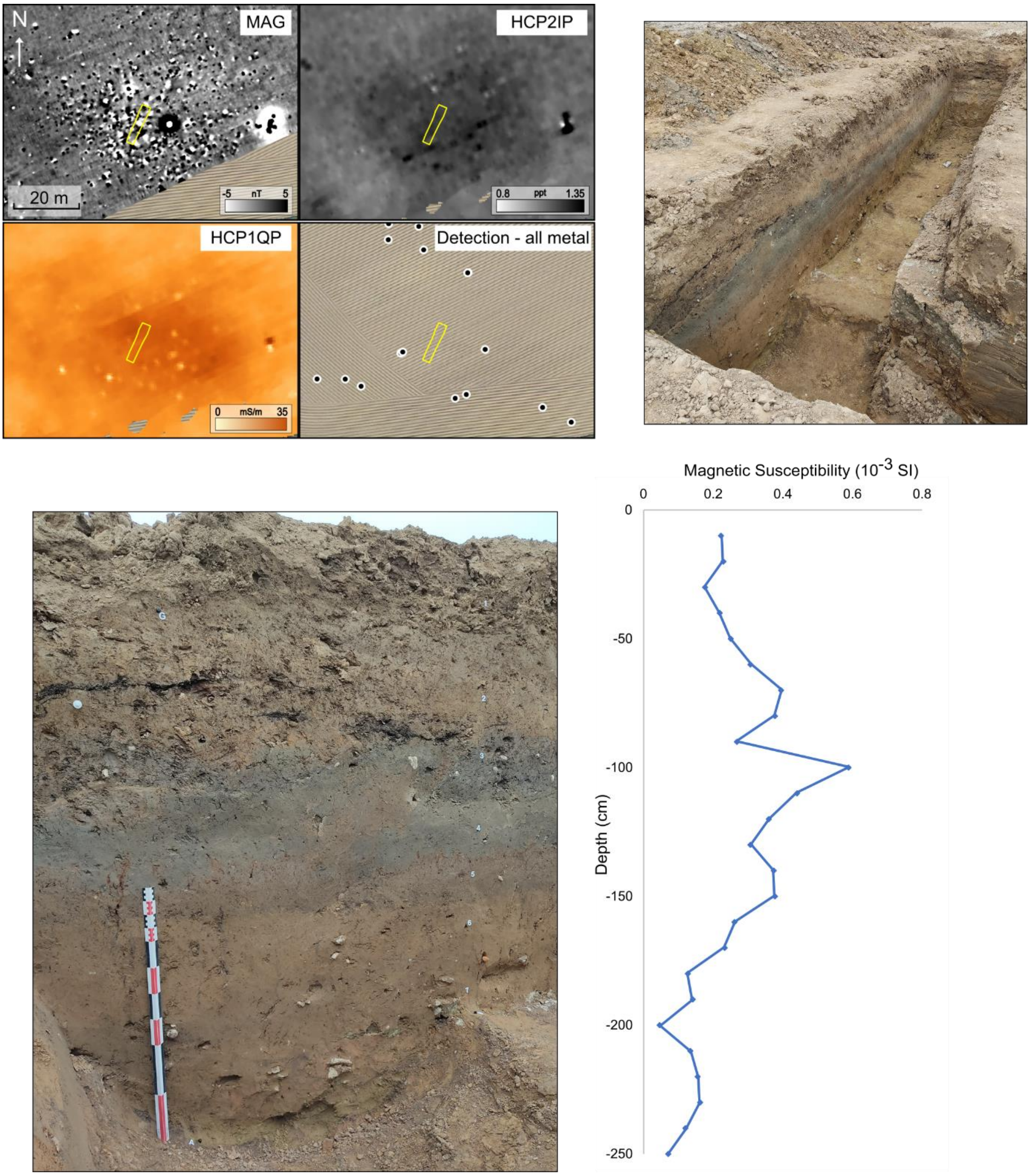

Figure 49: Large feature encountered at border of former wooded area near Hougoumont farm. Test excavations revealed a substantial pit feature. The susceptibility log shows a peak at a depth of 1 m with the enhancement related to a succession of ploughzones in colluvial deposits. Figures and photos by author.

Features relating to former parcel boundaries were also documented in the geophysical data. These are significant in the study of battlefields, as they potentially represent obstacles to movement, which is another important component of military terrain analysis (Babits 2014). These features seem to most commonly take the form of straight linear anomalies with low magnetic (in both FDEM and FM) and resistive (i.e., low conductivity) properties. Test excavation of one such feature revealed a 1 m wide ditch with a depth of at least 0.65 m, though it was not possible to uncover its full extent (Figure 50). This feature also corresponds exactly to the boundary between a former orchard and cultivated land shown on the Ferraris map. Thus, it seems that the ditch was backfilled with a more resistive (sandier) and less magnetic material, which is contrary to the situation often observed when a cut feature is filled with more magnetic topsoil over time creating a distinct positive magnetic anomaly (Gaffney and Gater 2003, p. 39). Another feature with a similar response is found in a field further south and correlates well with an 1816 map of the battlefield (Figure 51). Field boundary features are known to have highly variable magnetic responses depending on the exact configuration of ditch/bank features and materials employed (Gaffney and Gater 2003, pp. 123–124). Further work is needed to understand the exact mechanisms behind the creation of these features at the site but their similar appearance at several different locations suggests a consistent process.

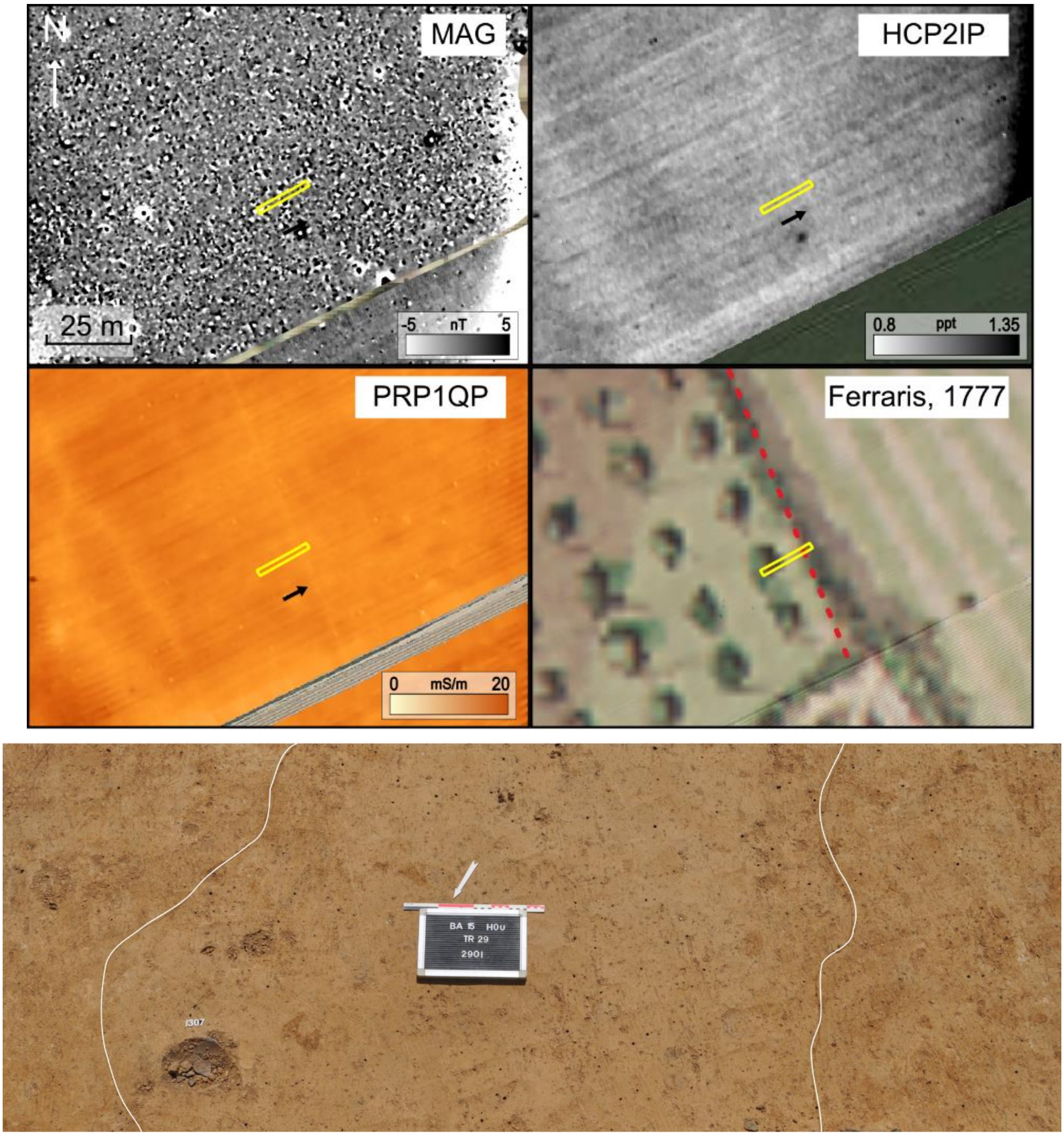

*Figure 50: Linear resistive and low magnetic anomaly (indicated by black arrow) revealed to be a ditch after test excavation (trench outline in yellow). The feature is most visible in the electrical data and is only faintly apparent in the magnetic datasets (particularly the magnetometry dataset, which has significant metal clutter). The location of the feature is shown as a dashed red line on the Ferraris map, correlating almost perfectly with the orchard boundary. Figures by author, Ferraris map (*Carte de cabinet des Pays-Bas autrichiens levée à l'initiative du comte de Ferraris*, 1771-1778) from Géoportail de la Wallonnie, photo courtesy of Waterloo Uncovered (used with permission).*

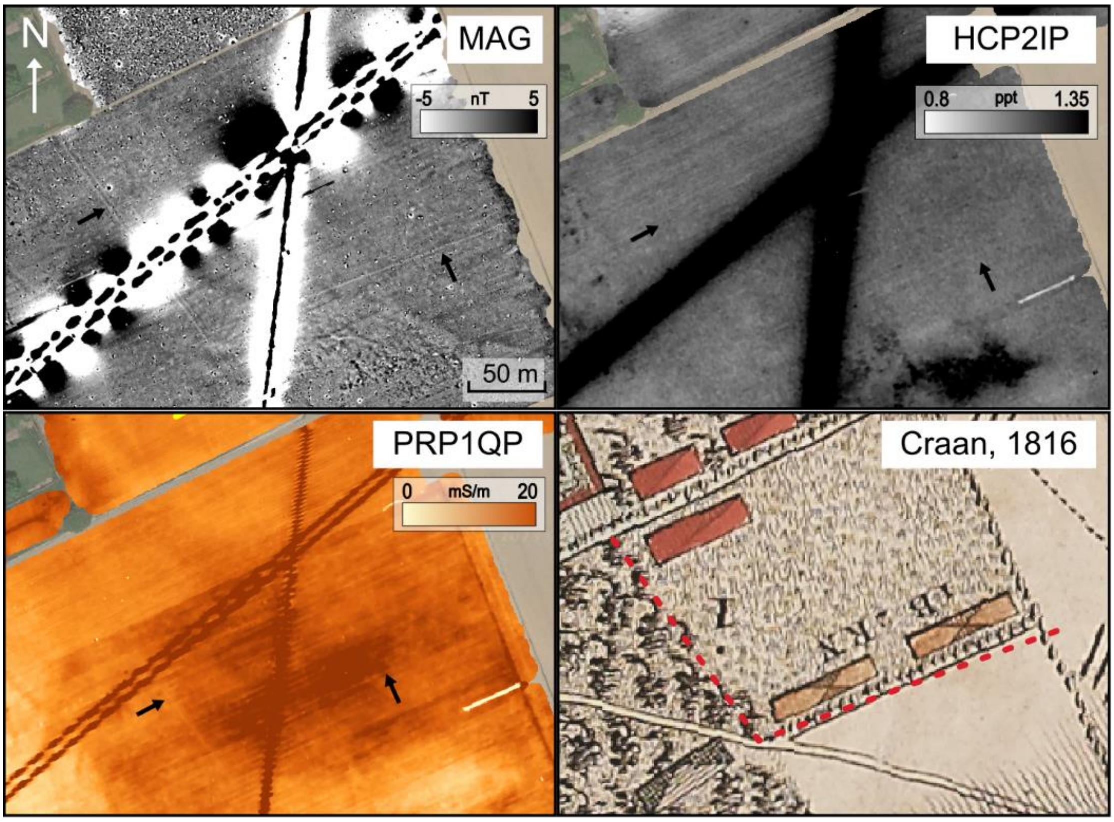

Figure 51: Linear low magnetic and resistive features (indicated by black arrows) that align with two parcel boundaries shown on an 1816 map (positions of geophysical anomalies shown as dashed red lines). Figures by author, Craan map from British Library Collections Item 31885, no copyright restrictions.

Further north on the reverse slope, a different kind of boundary feature is present with the more typical enhanced magnetic response (Figure 52). It correlates well with a former field boundary, shown on an 1841 cadastral plan and visible in aerial photos as recent as 1979. In this case, the feature is very evident in the IP component of the FDEM data but there is no contrast in the electrical data, suggesting minimal textural variability in the ditch fill. Interestingly, the feature is also not evident in the FM data, perhaps again due to the implicit high-pass effect. It is only faintly visible, particularly on its western/southern half, as a series of streaky discrete positive anomalies. Several gaps are visible in the anomaly in the FDEM data, possibly representing areas that have been ploughed out. One of the gaps also corresponds to the location of a track or path shown on the 1841 map. The lack of sign change in the HCP coil pairs suggests that the feature is quite shallow and this was confirmed by downhole MS measurements in several boreholes, which indicated enhancement below 50 cm (to 120 x10^-5 SI or approximately 2-3 x background value). No macroscopic differentiation of the ditch fill was visible in the borehole samples.

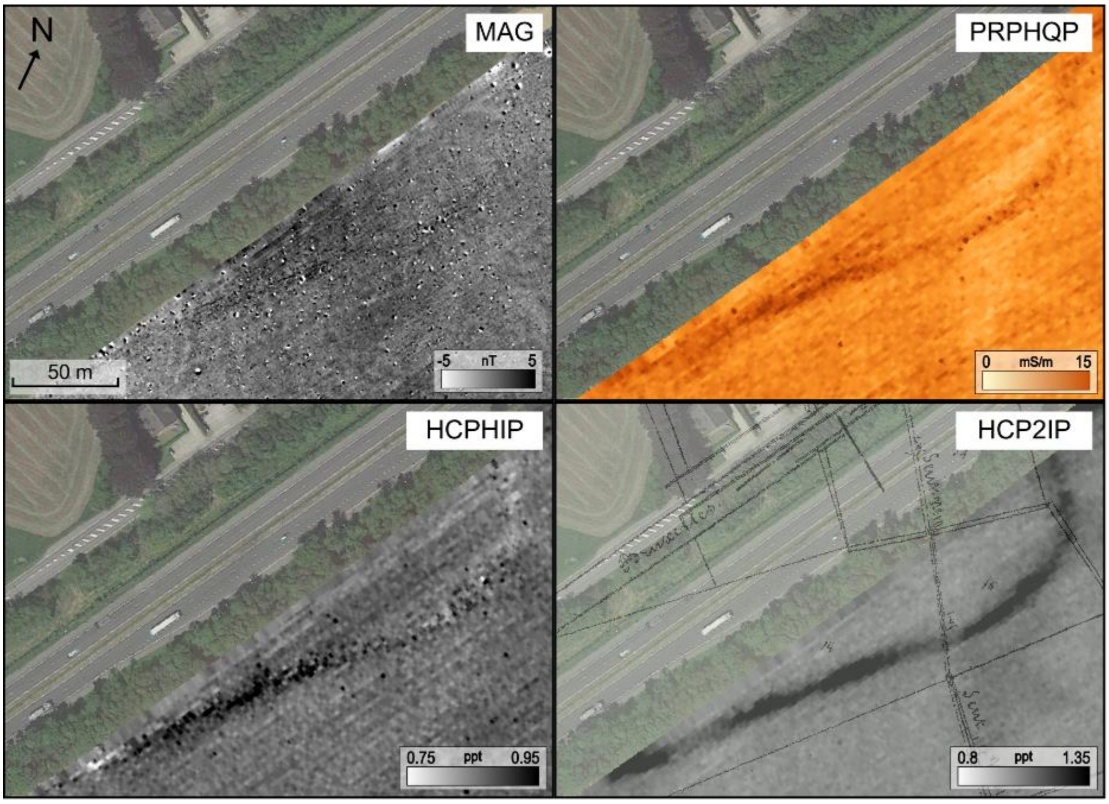

*Figure 52: Shallow ditch feature with a particularly strong response in the 2 m coil HCP coil pair and a subtler response in the FM data. The shallower coil pairs indicate concentrations of metal in the footprint of the ditch. It appears to match quite closely with a property boundary shown on an 1841 map, overlaid on the HCP2IP data. Figures by author, basemap Google Earth 2021, 1841 map from Géoportail de la Wallonie (*Atlas des Voiries Vicinales de 1841*).*

Environmental

This category encapsulates information about the natural soil environment that is relevant to the archaeological interpretation of a site. For Waterloo, the major application of the geophysical dataset for this purpose was the use of electrical data in the delineation of colluvial deposits on the basis of soil texture sorting. This has great relevance for the recovery of battlefield evidence at Waterloo, as significant recent soil erosion has potentially resulted in the movement of artefacts, damage to certain ephemeral features and deep burial/enhanced preservation of other features. This work is described at length in Chapter 5 and is thus not repeated here.

Discussion

The methods employed were effective at identifying a range of features of interest. The rapid identification of ferrous metal scatters allows for a preliminary comparison between areas and is a valuable complement to conventional metal detection. The central role of metal detection in battlefield archaeology is well-established (Banks 2020), but the use of other geophysical methods for mapping metal scatters has only been explored in a limited manner (e.g., Wiewel and De Vore 2018). Correlations between probable ferrous findspots extracted from FM datasets and lead findspots (the vast majority being musket balls) from conventional metal detection surveys suggest that the former can be used as a proxy for intensity of combat across the landscape. Contrasts between areas that can be linked to known differences in theatres of combat is very promising and suggests that similar inferences can be made in cases where the historical record is less clear. The persistence of these broad patterns across multiple seasons and despite intervening episodes of metal detection and major differences linked to modern landuse demonstrates the value of repeat surveys and their potential as a form of monitoring. A logical next step is to undertake modelling of the magnetic dataset specifically aimed at identifying objects of interest. This would be informed particularly by quantitative methods used for the discrimination of unexploded ordnance from clutter (e.g., Billings et al. 2002; Yan Zhang et al. 2003; Butler et al. 2012). Similar modelling procedures have also been used to a limited extent for 20th-century conflict sites (Saey et al. 2011; Stele, Linck, et al. 2023).

The identification of a range of other features shows the broad potential of the employed methods for detecting human activity. Some of these features have been shown to conclusively pre-date the battle (e.g., brick kilns involved in the construction of farm buildings) and are likely to have played a minimal role in it. Others seem to have been, at the very least, important landscape features at the time of the battle and may have played a direct role in the conflict (e.g., a quarry pit, various structures, parcel boundaries). Still others seem to have been involved in the direct aftermath (e.g., a mobile forge likely related to either battlefield clean-up or the construction of a memorial in the ensuing years). More recent features point to the continued use of the landscape and enduring legacy of the battle (e.g., reenactor-related features). Together, they have led to a better understanding of the development of the palimpsest landscape.

Despite these successes, other expected features were not conclusively identified, particularly those related to burial of the dead and evidence for encampments (with the caveat that not all potential features have yet been sampled). Potential reasons for this include historical particularities, insufficient sampling resolution (in the case of particularly small features), lack of contrast, and post-depositional influences. Ultimately, however, it remains necessary to document archaeological examples of these features and conduct appropriate sampling and measurement of geophysical properties *in situ* (e.g., Verhegge et al. 2021). This will allow for the forward modelling of the geophysical response and quantitative determination of whether a sufficient contrast exists, given instrument sensitivities, noise envelopes, and background characteristics (De Smedt et al. 2022). In the absence of this data, it can only be said at present that the expected features should theoretically be detectable based on their expected geophysical properties and the presence of other similar categories of features in the dataset. Further research will help to refine the range of detectable targets and their geophysical and archaeological expressions in different settings.

The FM data was particularly valuable, given that many of the targeted anomalies were magnetic in origin. The high spatial resolution, speed, sensitivity and robust available instrumentation and processing schemes combine to make it the most appropriate method assuming a suitable soil/geological setting. There may also be some benefit to the use of caesium magnetometers, given the low magnetic background of the loess environment. The higher sensitivity of these instruments over fluxgate sensors (Becker 1995, 2009) may allow for the recognition of more subtle (or deeply buried) features, particularly in total field mode. The FDEM data, despite the choice of a coarser spatial resolution, was highly complementary and provided additional information on feature depth and pedological variability that could not be obtained from the magnetometry data alone. The multi-method approach was thus important, as the combination of electrical and magnetic properties and different instrument sensitivities allowed for a more robust interpretation of feature character and geometry. The multi-coil geometry of the deployed FDEM sensor was important in this regard, as it allowed for an approximation of the depth of features of interest (De Smedt 2013, pp. 111–113), which was useful for the preliminary identification of superficial (and likely very recent) features.

In all, it can be seen that large-scale geophysical survey is an essential approach for the study of battlefield landscapes and represents the best (and indeed the only feasible) methodology for the first identification of possible subsurface features of interest in these landscapes. Many of the identified features are relevant to the story of the battle and would have been difficult to identify using other prospection methods, given the scale of the area of interest. The geophysical surveys at Waterloo have, in many circumstances, led to more questions than generated definitive answers. To this end, targeted sampling and (especially) archaeological excavation is crucial for a more complete understanding of the non-invasive dataset. This has allowed for proper contextualization of features in the broader palimpsest landscape and an understanding of the role of seemingly more tangential elements of the landscape in the battle and its aftermath.

Incorporating other forms of ancillary data (particularly historical evidence in its various forms, as well as geological and pedological information) is also crucial for overcoming one of the major complexities of geophysical data, which is the non-unique or equifinal nature of the data. This is particularly important in a complicated setting such as Waterloo, where the major episode of interest represents a tiny fraction of the entire landscape history. The importance of historical geospatial data for interpreting geophysical data from conflict sites has been especially well demonstrated in the integration of contemporary air photos for 20th-century sites (Note, Gheyle, et al. 2018; Note, Saey, et al. 2018; Stele et al. 2021, 2022; Stele, Linck, et al. 2023). While such an approach is evidently not possible in the case of earlier conflicts, the importance of historic maps has been shown here.

A major challenge of the applied methodology has been arranging access to survey areas. This is an increasingly relevant limitation in ground-based archaeological prospection with the now routine large-area surveys undertaken by motorized multi-sensor arrays. As has been frequently noted in recent years, the scale of terrestrial geophysical research in archaeology has increased from tens to hundreds of hectares (Trinks 2015). The compounding issues of arranging access to survey areas are significant challenges in highly parcelled arable landscapes, where the majority of such surveys take place. These practical challenges have not been extensively discussed in the literature (though see recent comments in Saito 2023, pp. 102–103) but have an important impact on the sampling design of large-area surveys.

For arable land following the typical crop rotation in temperate climates (e.g., Leteinturier et al. 2007; Aubinet et al. 2009; Zhou et al. 2022), it is generally possible to access fields in three main windows (Figure 53): 1) after the harvest of winter crops and (if planted) before green manure/cover crops (e.g., mustard) are too advanced (July-August); 2) at the peak of cover crop growth/before ploughing or after harvest of summer crops (e.g., potatoes) but before planting of the winter crop (October-November); and 3) prior to the planting of summer crops (e.g., sugar beets) in the case of fields left vacant over winter (March). These windows are evidently highly dependant on weather and can be shifted considerably due to periods of higher or lower precipitation. For the Waterloo surveys, a mean rate of 1.5 ha/h was achieved for the (motorized) magnetometry and (2 m interline) FDEM surveys.[16] Thus, approximately 200 additional working days (or 1200 survey hours) would be required to complete the entire 1000 ha area with both methods.

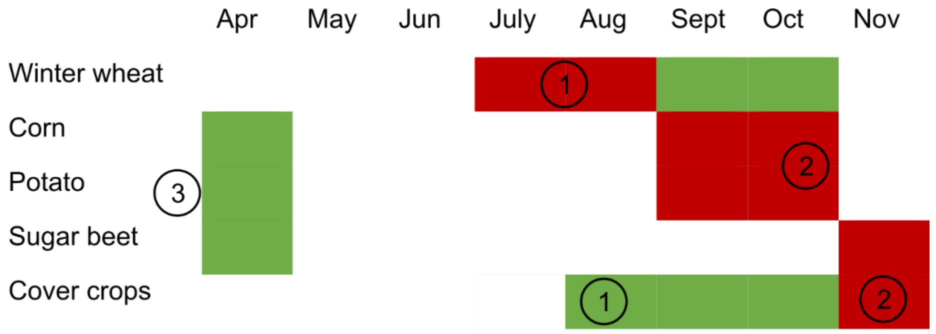

Figure 53: Typical crop cycle calendar for the most common crops in Belgium, with periods of planting/sowing (in green) and harvest (in red) (modified after Gobin 2018, fig. 1). In the case of cover crops (e.g., mustard), the crop is not harvested but ploughed into the ground. Numbers correspond to particular survey windows, as outlined above. Figure by author.

These considerations are especially relevant to battlefield sites (though not unique in the context of landscape archaeology), given their large spatial extent. A series of campaigns across multiple seasons or years should thus be envisioned and prioritization of certain areas or methods may be necessary depending on the scope and timeline of the project. It is worth noting that recent developments in the use of UAV-deployed geophysical sensors for archaeological surveys (Gavazzi et al. 2021; Schmidt and Coolen 2021; Stele et al. 2022) have the potential to alleviate some of these issues. Much of this research has focussed on magnetometer applications and direct comparisons with terrestrial surveys have shown great promise (Stele, Kaub, et al. 2023). While certain features are more difficult or impossible to recognize given the reduced sensitivity of drone-based surveys, speed and ease of access could outweigh the limitations, particularly in the case of reconnaissance surveys.

Conclusion

Large-scale geophysical surveys (fluxgate magnetometry and frequency-domain electromagnetic induction) at the battlefield of Waterloo have enabled the identification of a range of archaeological features, some of which appear to have direct relevance to the battle. Over 100 hectares of data were collected from various locations across the landscape. A complex palimpsest landscape has been revealed, providing fine-grained insights into the events of the battle and its aftermath. The combination of multiple forms of non-invasive prospection, ancillary information (historical data), targeted minimally-invasive sampling, and archaeological excavations is a promising integrative methodology for the study of extensive battlefield landscapes. The use of large-area geophysical survey in these environments is not without challenges: these largely revolve around the limited windows of land access in intensively utilized landscapes. Further work also remains to be done in the context of establishing the geophysical properties of ephemeral archaeological features from battlefields. This will enable the refinement of

[16] For manual (walking) magnetometry surveys, a rate of 0.5 ha/h was achieved and 0.6 ha/h for 1 m interline FDEM.

survey methods and define the limits of what can be gleaned from the prospection of these sites. As our understanding of the archaeological records and geophysical expressions of these sites grows, more structured interpretations of geophysical data can then be undertaken. The findings suggest that, despite the challenges still to be overcome, large-scale geophysics is an essential component of the investigation of battlefield sites.

Chapter 5: Minimally-Invasive Approaches to the High-Resolution Mapping of Colluvial Deposits at the Battlefield of Waterloo: Implications for Archaeological Practice

This chapter is based on a manuscript titled *Minimally-Invasive Approaches to the High-Resolution Mapping of Colluvial Deposits at the Battlefield of Waterloo: Implications for Archaeological Practice* by Duncan Williams, Kate Welham, Stuart Eve, and Philippe De Smedt. Modifications here include a reduced background to Waterloo and the geophysical survey methodology, expanded description of the optical remote sensing workflow, expanded background on soil erosion mechanisms, insertion of GPR/ERT/magnetic data with discussion, and several additional figures/examples.

Introduction

Soil erosion is the process of soil detachment and movement, primarily by the action of wind, water, and tillage (Pennock 2019). Water erosion is the most widespread type, while wind erosion occurs primarily in arid and semi-arid environments. Other important erosional agents include glacial (related to the hydrological cycle) and coastal processes (driven by waves and currents associated with wind energy) (Lupia-Palmieri 2004) but will not be considered here. Colluvium refers to deposits that form as a result of erosion.[17] Definitions of colluvium typically includes two types of materials that result from quite different processes: slope deposits associated with surficial flow/creep movement and mass wasting deposits associated with mass movements (e.g., landslides) (French 2016; Mücher et al. 2018); here the focus is on the former.

The United Nations recently outlined the global impact of soil erosion in a report produced as part of the Global Symposium on Soil Erosion (FAO 2019). It is universally agreed that soil erosion has been greatly accelerated by anthropogenic activity, with devegetation and intensive agriculture being two particularly important factors (French 2016). Indeed, long-term archives of colluvial deposits, which enable reconstruction of past landuse, have demonstrated increased erosion in the recent past (Kappler et al. 2018). Continued soil degradation increases the risk of extreme environmental events (e.g., mass wasting), while impacting global food security and water quality. Recent work in landscape and environmental archaeology (e.g., Turner et al. 2020; Brandolini et al. 2023) has demonstrated the contributions of examining past landscape management practices in light of environmental impact and ecological sustainability.

Alongside threats to other ecosystem services outlined above, soil erosion has been cited as a critical threat to global archaeological heritage. While coastal erosion heavily linked to climate change has been a prominent focus (Dawson et al. 2020), the impact of other forms of erosion (wind, water, and tillage) in arable landscapes has also been extensively acknowledged (Meylemans et al. 2014).

[17] Note that there is considerable variety in the published definitions of the term colluvium (see Miller and Juilleret 2016; Zádorová and Penížek 2018).

Indeed, nearly two decades ago, plough-induced soil erosion was noted as being the greatest threat to archaeological sites around the world (Wilkinson et al. 2006).

Soil erosion and the post-depositional movement of artefacts, which may be entrained in colluvial deposits (French 2016), is particularly problematic for archaeological research which relies on the interpretation of spatial distributions of surface or near-surface finds. One such area is battlefield archaeology, where the major focus is on the analysis of spatial patterning of conflict-related items recovered from the ploughzone or topsoil (Banks 2020). Surveys are undertaken using conventional metal detectors that typically have a maximum depth of exploration of approximately 30 cm (Connor and Scott 1998, p. 79). Thus, objects that are buried beneath even a relatively shallow layer of colluvium may be undetectable. This is also problematic for other forms of archaeological prospection (e.g., test pitting) and has been a frequent challenge for archaeologists working in complex geomorphological environments (particularly fluvial and alluvial) (e.g., Weston 2001; Layzell and Mandel 2019; Crabb et al. 2022).

While erosion can degrade archaeological features and transport objects from their depositional context, it also has the potential to seal other deposits *in situ*, possibly affording them some level of protection from plough damage, bioturbation, etc. In both cases, knowledge about the existence and extent of colluvial (eroded) deposits is beneficial to the understanding and management of archaeological landscapes. Furthermore, archaeologists have long recognized that colluvial deposits are themselves excellent archives of human landuse and are thus important targets for environmental archaeological research enabling chronological sequencing and perspectives on long-term human-environmental interactions (e.g., Vanwalleghem et al. 2006; Froehlicher et al. 2016; Henkner et al. 2018). This chapter will examine methods for characterizing colluvial deposits at the detailed scale required for archaeological purposes. Thus, the focus is not on predicting/modelling future erosion or the quantitative characterization of soil loss (which has been extensively studied by other researchers (Boardman and Poesen 2006)) but the characterization of existing colluvial deposits and their relation to the archaeological record.

Background: Mechanisms of Soil Erosion and Research Approaches

Water erosion (detachment, transport and deposition of soil with water) (French 2016; Ahmed et al. 2019; Pennock 2019) is the dominant form of erosion in temperate climates and the main mechanism responsible for soil erosion in the case study considered herein (Verstraeten, Poesen, Goossens, et al. 2006).

Raindrop impact causes initial soil detachment, along with overland flow (Pennock 2019). When the infiltration capacity of the soil is reached, surface flow occurs, and detached particles are transported (sheet erosion). Weather patterns play a large role; larger raindrops have higher velocity (Ahmed et al. 2019, p. 50) causing greater detachment, while rainfall intensity impacts infiltration. High-intensity but infrequent rainfall events are often responsible for the majority of soil erosion, particularly in periods where vegetation cover is negligible (e.g., fallow period in cultivated fields) (Steegen, Govers, Nachtergaele, et al. 2000). In certain climates, snowmelt is also an important contributor to runoff.

As the water flows, it forms small incisions (rills), wherein the velocity increases and flow is concentrated. This starts the process of channelized erosion, which begins as rill erosion but can reach a greater extreme in the form of gully erosion. Rills and gullies are part of the same process but can be differentiated from one another on the basis of size (Poesen 1993; Ahmed et al. 2019) and recurrence, with the former generally filling in naturally and changing position over time (self-stabilizing) and the latter tending to remain in the same position (self-perpetuating) (Gao 2013). Another category termed ephemeral gullies is intermediary between the two and describes less permanent gully forms (Nachtergaele et al. 2002). These are often filled during tilling operations but reoccur subsequently in the hollows that remain. Another important differentiator is that rills only occur on hillslopes (with relatively gently slopes above 2°), whereas gullies often occur in valley bottoms or on steeper hillslopes (above 8°) (Gao 2013). Tunnel or piping erosion can also occur in the subsurface, where water flow concentrates in animal burrows or cracks, and lead to gully formation, though this is responsible for only a small portion of soil erosion by water (Pennock 2019).

Detachment and transport are determined by the resistance of soil particles to hydraulic flow. Conversely, when the flow of particles in motion decreases past a critical point, deposition occurs. This is primarily determined by slope steepness (which influences runoff velocity), such that deposition takes place at the base of the slope. Topography is thus the primary factor influencing erosion potential. Erosion can occur in any location that has greater than 2° of slope (French 2016, p. 157) and is directly related to steepness in slope. The configuration of the slope also has an impact, with flow concentrating in slope concavities if they are present. In the absence of across-slope variability, erosion will be greater at the bottom of the slope where velocity and depth of runoff is greater (Pennock 2019, p. 37).

The soil type has an impact, as differential transport occurs in water erosion, with soil texture being the primary factor. Clay particles resist detachment because of the high cohesion between them, while medium to larger sand particles resist transport because of their large size. Grain sizes of approximately 0.5 mm (coarse silt to fine sand) are the most susceptible to erosion (French 2016). Other properties such as soil organic content, structure, roughness, and permeability also have an impact on erodibility (Pennock 2019).

Vegetation cover also has a great impact, beginning with the interception and slowing of raindrops, increasing infiltration rate and soil resistance through root action, and blocking overland flow. The amount of cover is directly related to the degree of soil loss, with the type of cover also playing a role (e.g., greater resistance to erosion moving from cropland to grassland to forest) (French 2016).

Lastly, landuse has an important influence and is closely linked to vegetation cover. It has also been demonstrated that tillage operations are responsible for their own form of erosion, causing downslope movement of soil primarily due to gravity. This increases exponentially with the depth of ploughing and speed of equipment. Other factors such as tillage direction and implement type also have an important influence (Van Oost et al. 2006). This mechanism differs significantly from water erosion; it does not result in net soil loss at the field scale but can transport soils to positions more susceptible to further movement via water erosion (Pennock 2019, pp. 31-33,42-44).

Much of the research dealing with soil erosion has focused on developing models for assessing future erosion risk and measuring and predicting soil loss (Brazier 2013). Foremost among these is the

Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and its derivatives, which is a widely-used empirical determination of the contribution of various factors (rainfall/runoff, soil properties, slope, landcover, and management practices) to overall soil erosion. The model has also been used in archaeological contexts to examine how landuse has impacted soil erosion in the past (Hill 2004; Brandolini et al. 2023).

The identification of existing colluvial deposits, especially those that are not particularly recent, has received less attention. They are typically mapped as part of regional soil surveys (undertaken with systematic field sampling), but these are relatively coarse and usually designed to be mapped at a scale of approximately 1:20,000. When higher-resolution data is sought, researchers may undertake their own sampling schemes (e.g., French et al. 2007), though this can be quite time-intensive. Another limitation of regional soil surveys is that they tend to be legacy data, (typically undertaken around the mid-20th century) and perhaps not adequately representative of dynamic processes such as soil erosion. Digital soil mapping is now a widely used technique that attempts to bridge this gap and ease some of the challenges associated with traditional soil surveys. It involves numerical modelling of soils in space and time using quantitative soil properties, as well as environmental variables (covariates) that influence soil formation (Hartemink et al. 2008).

As part of this initiative, researchers have relied on a variety of non-invasive observation methods for mapping soil erosion. Since topography is one of the foremost determinants of soil properties and has a critical role in soil erosion and accumulation (Schaetzl 2013), terrain derivatives obtained from elevation models constitute one of the most important and widely used predictors of colluvial deposits (Zádorová et al. 2014; Penížek et al. 2016; Đomlija et al. 2019). The widespread availability of high-resolution elevation models from LiDAR surveys has greatly enabled such work. Alongside the topographic information produced by LiDAR data, the raw intensity data has also been shown to have some value in characterizing landcover and soil properties (Challis et al. 2011; Garroway et al. 2011).

Other forms of remote sensing have also been used to identify colluvial soils as part of larger efforts in digital soil mapping. Most applications focus on the use of passive optical remote sensors operating in the visible and near-infrared range. The manual interpretation of air photos, which revolutionized conventional soil survey (Ahrens 2008), is an example of such an approach and has long been used for mapping erosional features (Hills 1950; Ray 1960), including for archaeological purposes (French et al. 2007). Results of analyses of air photos for defining erosional features compare well with field survey data (Nachtergaele and Poesen 1999). It continues to be an important method for detailed mapping of erosion, given the high resolution of most images and also allows for the analyses of change over time if appropriate images from different periods are available (Jenčo et al. 2020; Netopil et al. 2022). As with many other geospatial applications, this has been greatly enabled by the widespread availability of affordable UAVs, permitting bespoke extremely high-resolution surveys and the production of topographic models alongside orthorectified images (Meinen and Robinson 2020; Oh et al. 2020; Malinowski et al. 2023).

Recently, there has been a focus on the integration of multi- and hyperspectral optical remote sensing data for a variety of soil mapping applications (Boettinger et al. 2008). Hereby, environmental covariates (vegetation, landuse, etc.) influencing soil patterns are identified based on their spectral signatures. A common application has been the characterization of soil texture using a variety of band ratios or indices with classification aided by machine learning techniques and analysis of field samples (e.g., Liao et al. 2013; Gholizadeh et al. 2018; Vaudour et al. 2019). The use of remote sensing indices for geoarchaeological modelling in alluvial environments characterized by deeply buried deposits has also been demonstrated by Crabb et al. (2022). Similar methods have also been used to characterize soil erosion with optical remote sensing data (Žížala et al. 2019).

Other types of remote sensing data such as synthetic aperture radar or thermal sensors are often incorporated into such analyses as well (Bousbih et al. 2019; John et al. 2022), as they are particularly sensitive to soil moisture. Soil mapping with remote sensing has been particularly enabled by free and open access to data from global missions such as Landsat and Sentinel platforms and, more recently, access to large databases of cloud-hosted images and processing libraries such as Google Earth Engine (Gorelick et al. 2017). The latter enable the production of more robust multi-temporal composites that are especially useful for applications examining long-term expressions of subtle landscape features (e.g., Orengo and Petrie 2017) or soil properties (Sorenson et al. 2022), as well as applications focusing on change detection such as landslide mapping (Lindsay et al. 2022).

Geophysical instruments, which measure variations in (primarily electromagnetic) physical properties that can be linked to soil properties (e.g., texture), have also been incorporated into soil mapping approaches and have been particularly effective at producing high-resolution maps of soil variability at the field scale (Brogi et al. 2021). Crucially, geophysical methods offer a means of balancing the limitations of scale that characterize point measurement (difficulty capturing heterogeneity) and remote sensing (coarse resolution and low depth penetration) datasets (Garré et al. 2023). In this regard, they could similarly be of use in soil erosion studies that struggle to bridge the gap between field observations and regional modelling based on plot experiments (Boardman 1998). They have, however, rarely been used explicitly to map colluvial deposits and erosional features[18], despite being very adept at measuring important variables related to soil erodibility (such as moisture and texture). GPR and other profiling techniques such as resistivity and seismic methods have been used for mapping and assessing mass movements such as landslides (Bichler et al. 2004; Sass et al. 2008) but in these cases are clearly aimed at deposits with considerable heterogeneity, possessing larger contrasts.

The following sections will compare the information derived from these different methods – manual sampling at point measurements, terrain modeling, remote sensing, and geophysical survey - using select locations at the battlefield of Waterloo as a case study. Each method has benefits and drawbacks related to the sample support, sensitivity, and cost associated. Combining different data sources allows for a more comprehensive understanding of depositional sequences than a single method affords.

[18] Some limited exceptions include the use of ground-penetrating radar for mapping thickness of colluvial deposits and distinguishing them from other soil layers, which has been successful in a variety of contexts (e.g., Aranha et al. 2002; Gerber et al. 2010).

Case Study: Battlefield of Waterloo, Belgium

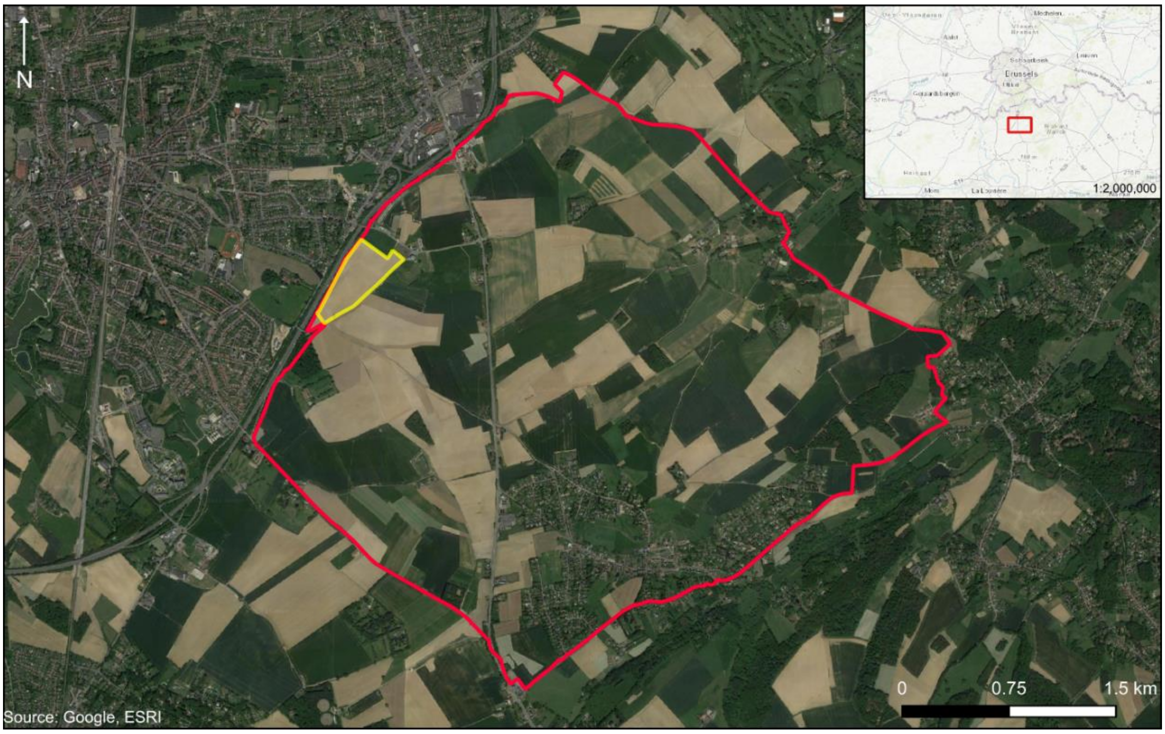

Figure 54: Location of study area. The highlighted parcel (Area A) is considered in additional detail. Figure by author.

The present landscape of the battlefield of Waterloo (Figure 54) is primarily used for agricultural purposes, as it was at the time of the battle. The site is situated in the periglacial Late Pleistocene loess belt of northwestern Europe, part of which runs through central Belgium (Haesaerts et al. 2016; Lehmkuhl et al. 2021). Beneath the loess cover, there is a sandy Tertiary substrate dating to the Middle Eocene (ca. 50 Ma) and originating from a series of marine transgressions (Laga et al. 2002; Houthuys 2011). Soil surveys were undertaken in the 1950s and 1960s (Louis 1958, 1973), involving boreholes excavated to a depth of 1.25 m at regular intervals of 75 m. These have shown that the thickness of the loess cover is quite variable due to the undulating nature of the topography, which is composed of a series of elevated ridges separated by intervening valleys (with maximum elevation differences of ca. 40 m). On the plateaus, the loess cover can be several metres thick, while the Tertiary substrate is present on the surface in steeply sloped areas due to erosion of the former. Colluvial deposits are present in concavities and at the base of slopes, where the eroded loess cover has been redeposited (Louis 1973, pp. 11–12). Approximately 85% of mapped soils in the study area are noted as being silty in texture with the remainder either sandy or silty-sandy (Service public de Wallonie 2005) in strongly eroded areas.

The typical soil profile in the study area is a Luvisol (Dondeyne et al. 2014), formed under mixed forest in the post-glacial period (Louis 1973, pp. 26–28). These soils feature a clay-enriched (illuviated) B-horizon beneath a decalcified, clay-poor (eluviated) A-horizon caused by downward transport (leaching) of clay particles by rainwater. This B-horizon sits atop the unaltered loess parent material (C-horizon). After deforestation, the original A-horizon was removed by erosion in most areas (except those with slopes of less than 1°) and replaced with an anthropogenic ploughzone (Ap horizon). Colluvial deposits formed through water erosion are typically silty with a uniform texture similar to the upslope deposits from which they derived (Louis 1973, pp. 20–21). Extent and thickness are variable and determined by the slope character and timing of deforestation. Textural B-horizons (Bt) have not formed in colluvial deposits: instead, the Ap horizon sits directly atop the C-horizon (which may itself cover another series of buried horizons) (Louis 1973, p. 31).

The Belgian loess belt is highly susceptible to soil erosion, with water and tillage erosion being the primary mechanisms (Verstraeten, Poesen, Goossens, et al. 2006, pp. 389–400; Rommens et al. 2007), as has been observed in the study area (Figure 55). Erosion has been associated with long-term cultivation in the study area and is not solely a recent phenomenon. Indeed, studies of historic erosion throughout central Belgium have suggested that a cultivation period of 2000 years (i.e., since the Roman period) should be considered when calculating long-term erosion rates (Verstraeten et al. 2006, p. 389). Time of deforestation is uncertain but based on the late 18th-century Ferraris map (Vervust 2016), the study area was largely devoid of trees by the time of the Battle of Waterloo. Net soil loss for the central Belgian loess belt has been estimated at approximately 26 tons per hectare per year, which equates to a soil profile lowering of 1.73 mm per year for a typical topsoil (Meylemans and Poesen 2014). This occurs primarily through rill and gully erosion, with sheet erosion estimated to represent about 10% of soil loss in the loess belt (Verstraeten, Poesen, Goossens, et al. 2006, p. 398). Ephemeral gully erosion is thought to be the dominant mechanism, accounting for roughly 50% of net loss (Vandaele et al. 1996; Nachtergaele et al. 2002).

Figure 55: Example of active rill erosion in study area, south of Hougoumont farm. Photo by author.

Whereas water erosion has been the dominant historic mechanism of soil loss in the loess belt, tillage erosion has increased in significance with the introduction of mechanized agriculture (Van Oost et al. 2006; Verstraeten, Poesen, Goossens, et al. 2006, p. 400). Since the 1950s, it is the dominant process responsible for landscape alteration in central Belgium. The impact of tillage increases approximately fivefold when moving from non-mechanized to mechanized implements (Van Oost et al. 2006), with a separate increase of approximately 50% since the 1950s (Verstraeten, Poesen, Goossens, et al. 2006, p. 400). Lastly, a phenomenon known as crop harvest erosion has also been recognized as an important mechanism of soil loss in central Belgium (ibid, p. 401). This occurs when soil clods stick to root and tuber crops (particularly potatoes and sugar beet) during harvest and are removed from the field.

Archaeological excavations have demonstrated that significant soil erosion has occurred in certain areas since the time of the battle (ca. 200 years), with accumulation of >1 m in some areas (Figure 56). While this overburden is not as extreme as that encountered in many alluvial environments (e.g., Verhegge et al. 2016), it nonetheless poses challenges for metal detection with conventional instruments and is sufficient enough to necessitate approaches other than manual excavation in some cases.

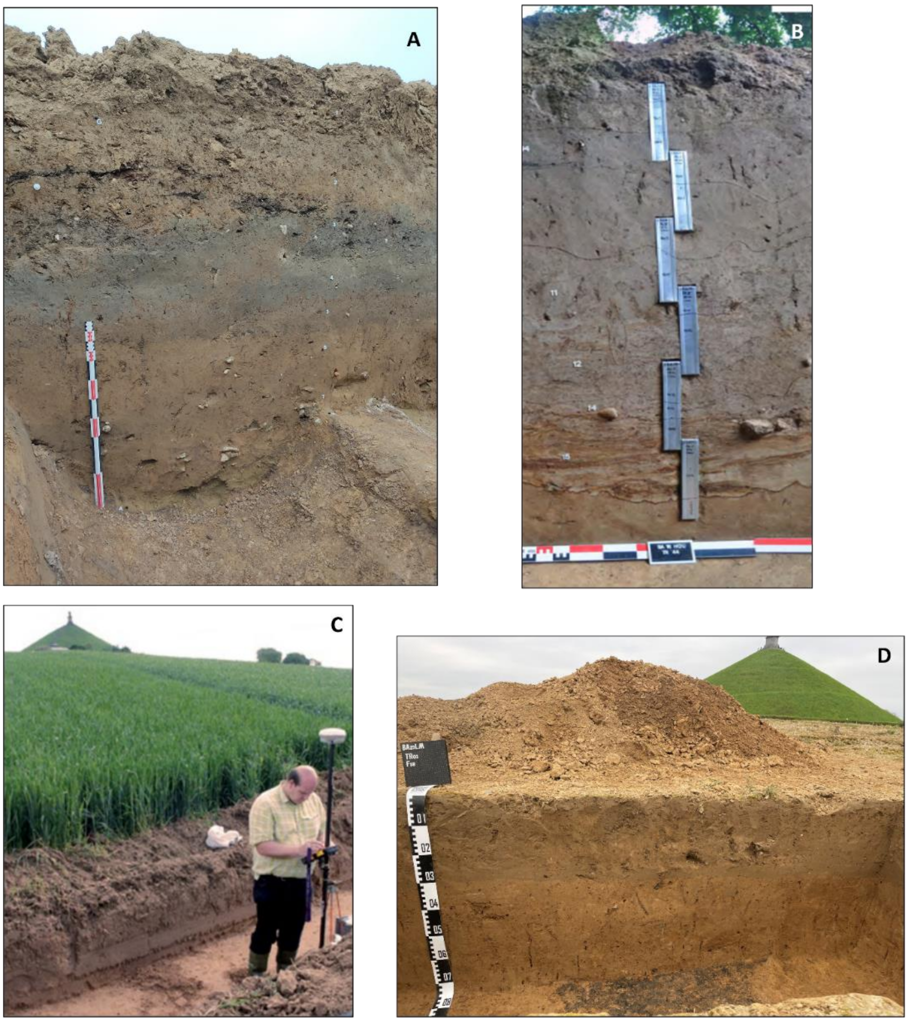

Figure 56: Examples of colluvial deposits covering archaeological features of interest. A: quarry pit open at the time of the battle (photo by author); B: covered way near Hougoumont farm (photo courtesy of Waterloo Uncovered, used with permission); C: trench near current visitor parking lot where an isolated burial was

discovered (Bosquet et al. 2015, used with permission); D: remains of a forge near the Lion Mound monument (photo by author).

Throughout the following sections, reference will be made to a ca. 14 ha subset of the larger study area, located in the northwest of the site (Area A, Figure 54). At present, it is entirely used for agricultural purposes and is characterized by considerable homogeneity in soil types, with the entire area classified as silty and well-draining.

Methods

To assess high-level erosion risk in the study area, factors outlined in the USLE are considered. Due to the relatively small size of the study area, the effect of rainfall erosivity is assumed to be constant. Landuse and support practices can also be treated as fixed variables because agricultural practices (partly governed by legislative policies) are consistent across the area and it has been largely deforested since the time of interest (i.e., 1815). If the objective was to explain variable inter- or intra-field erosion rates on a yearly or seasonal basis, these factors would have to be considered; however, because the focus is on long-term depositional processes, this small-scale variability can be ignored. While soil texture is also largely homogenous in the study area (with 85% of soils classified as silty), influence of slope position on depth to Tertiary sands (Louis 1958) links it closely to topography. This makes topography a key factor for examining long-term erosion susceptibility.

One of the limitations of the USLE for the present exercise is that it does not indicate areas of likely deposition (i.e., colluvium) (Van Oost et al. 2000, p. 578). To address this, an approach to extract topographic landform elements is required. Here, the interest is in extracting footslope and toeslope areas where colluvial deposition is most likely (Schaetzl 2013) (Figure 57).

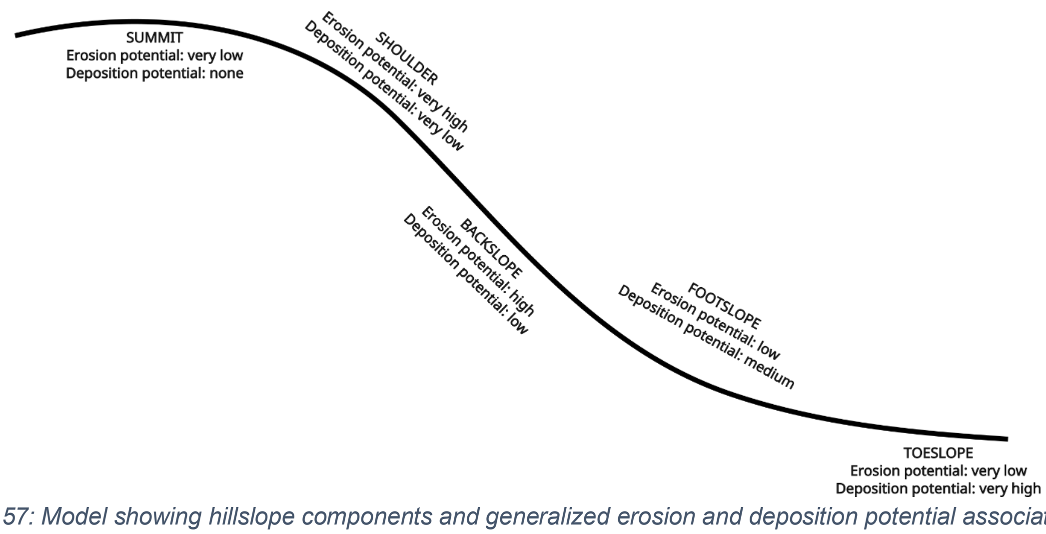

Figure 57: Model showing hillslope components and generalized erosion and deposition potential associated with each. Modified from Schaetzl (2013, fig. 3).

The geomorphons method, based on the classification of landforms from a terrain model using ternary pattern recognition of elevation differences and line-of-sight (Jasiewicz and Stepinski 2013), was used to achieve this. From this classification, a total of 498 possible terrain patterns (geomorphons) are identified, which can be reduced to 10 common landform elements based on correlations between them. For this analysis, the 10 landform elements were then further reduced to three hillslope categories relevant to soil erosion: accumulative/depositional zones (made up of pits, valleys, footslopes, and hollows), erosive zones (peaks, ridges, shoulders, spurs, steep slopes) and stable zones (flat areas, gentle slopes). Important parameters that influence the result of the geomorphon classification are the lookup distance and flatness threshold. The former defines the search distance for each cell and in practice determines the largest recognizable landform element (here, 25 m). The latter provides the decision threshold at which a cell is classified as being equal in elevation to the focal cell. Here, a value of 2° is used, following the slope threshold noted above. The terrain model used is a LiDAR dataset collected in 2013-2014 with a measurement density averaging 0.8 pulses/m^2 (Service public de Wallonie 2015).

The geomorphons method generates a risk/likelihood of erosion model but does not directly identify and characterize existing colluvial deposits. For this, a contrast must exist, operating from the assumption that colluvial deposits possess measurable soil properties that can differentiate them from other (background) deposits. These differing soil properties (e.g., texture or organic matter content) are also likely to affect vegetation growth (Groß et al. 2023). To explore this, several remote sensing products are assessed. First, a range of high-resolution orthophoto scenes dating back to 1971 are considered (pixel resolution of at least 1 m, improving to 0.5 m starting in 2001 and 0.25 m starting in 2009). Colluvial deposits and eroded areas can be identified in certain areas of the images through visible contrasts in brightness, colour and texture.

These contrasts are, however, inconsistent across various images, depending on the seasonal and landuse conditions (especially crop type and phenological stage) at the time of image capture. This problem has previously been recognized by researchers attempting to delineate long-term landscape features. A proposed solution has been to use multi-temporal image composites (Orengo and Petrie 2017). Here, Google Earth Engine was used to produce Landsat-8 (L8) and Sentinel-2 (S2) optical remote sensing image composites. Characteristics of each sensor are shown in Table 3. These two different sensors were used to assess the impact of spatial resolution on the delineation of the features of interest. Overlap in radiometric and temporal range of the two products allows for such a comparison. Top-of-atmosphere (TOA) reflectance products were used for both sensors. Bottom-of-atmosphere (BOA) or surface reflectance (SR) products with atmospheric corrections were also assessed but found to show no significant differences for the purposes of this analysis. While it has been shown that atmospheric correction results in a relative increase of vegetation indices and can introduce errors that vary depending on landcover class (Seong et al. 2020; Rech et al. 2023), this did not hinder the results here. TOA images were thus selected because an additional 21 months of imagery was available for the S2 sensor (available from June 2015, as opposed to SR images available only from March 2017).

Table 3: Key characteristics of Sentinel-2 and Landsat-8 sensors.

	Sentinel-2	**Landsat-8**
Spatial Resolution	10 m	30 m
Radiometric Resolution (central wavelengths of optical bands)	B2: 492.4 nm (Blue) B3: 559.8 nm (Green) B4: 664.6 nm (Red) B8: 832.8 nm (NIR)	B2: 480 nm (Blue) B3: 560 nm (Green) B4: 655 nm (Red) B5: 865 nm (NIR)
Temporal Resolution	5 days (2-3 at mid-latitude)	16 days

Launch Date	June 2015	February 2013
Number of unique images used in multi-temporal composites	662	285

Cloud-free composites were produced using the bitmask cloud bands provided by each sensor product. For S2, these are based on the blue and shortwave-infrared bands (downsampled to 60 m) and are used to identify pixels likely to contain opaque or cirrus clouds (European Space Agency 2015). A 'cloudy-pixel percentage' variable is then assigned to each image, which can be used for initial filtering of an image collection. A relatively large threshold of 80% for this variable was used to increase the image collection size during initial filtering. This is larger than the 20% threshold applied in the Earth Engine documentation (Google n.d.), which is often replicated in other studies (e.g., Orengo and Petrie 2017), but was used here because the area of interest is quite small compared to the overall tile size of each S2 image (110x110km), and it is located at the intersection of two tiles. Increasing the sample size did not hinder the results of the cloud masking. Thus, even images with quite high cloud cover could still contain usable data after masking. Another method for cloud masking was trialed with S2 data using the s2cloudless algorithm (Zupanc 2017) which considers cloud shadows and uses a higher-resolution cloud probability band. This has been shown to be a high-performing algorithm in comparisons of various cloud-masking methods for S2 data (Skakun et al. 2022). It resulted in improvements when viewing individual images but generated noise and similar artefacts in composites. Thus, masking with the QA (quality) bitmask band supplied with each image appears to be an acceptable method for larger sample sizes.

A mean pixelwise reducer was used to produce the multi-temporal composite after cloud masking, whereby the mean reflectance value is taken from the image stack for each band. The mean reducer produced a more homogenous image than the median, which resulted in more within-field noise and complicated the delineation of contrasts, particularly when dealing with the smaller image collections for sub-periods, as outlined below.

To further enhance contrasts in the image composites, non-visible bands of the multispectral instruments were used to compute spectral indices. Vegetation indices are widely used to assess vegetation health, based on the increase in reflectance that occurs in the near-infrared part of the spectrum owing to the presence of leaf pigments in healthy vegetation (Jensen 2014, chap. 11), with the Normalized Difference Vegetation Index (NDVI) being the most commonly applied. The Enhanced Vegetation Index (EVI), which corrects for some atmospheric and soil background effects , was initially used here, following the protocol outlined by Orengo and Petrie (2017), but further trials indicated that nearly identical results are obtained using NDVI. This may be because the EVI primarily offers improved sensitivity in areas of particularly high biomass (Jensen 2014, p. 393).

Following Orengo and Petrie (2017), bimonthly seasonal composites were produced based on rainfall amounts to heighten contrasts which might relate to seasonal moisture availability. Monthly composites were also attempted but the smaller sample sizes resulted in remanent cloud effects from misclassified pixels during masking (persistent despite varying cloud masking methods and thresholds, as noted above). Monthly precipitation data was obtained from the Royal Meteorological Institute of Belgium for the local commune for the period 1991-2020 and bimensal periods were classified as belonging to either the wet or dry season. On this basis, the wet season is defined as comprising the bimensal periods of January-February, July-August, and November-December, while the dry season comprises March-April, May-June, and September-October. Vegetation indices are calculated on the resulting mean image from each period. For visualization of the results, a false-colour composite is created for each season (wet and dry), whereby a bimensal image is assigned to each of the R, G, and B bands.

Geophysical survey was also used to characterize intra-field variability at higher resolution and for more direct assessment of soil properties. Frequency-domain electromagnetic (FDEM) survey was used in a multi-coil configuration, which allows for simultaneous evaluation of electrical conductivity (EC) and magnetic susceptibility (MS) at different depths. The instrument used was the DualEM-21H (DualEM, Canada), equipped with a transmitting coil operating at 9 KHz and three pairs of receiving coils oriented horizontally coplanar (HCP pairs at 0.5, 1, and 2 m spacing) or perpendicular (PRP pairs at 0.6, 1.1, and 2.1 m spacing) to the transmitting coil. This renders so-called apparent values (ECa and MSa, respectively), which assumes a homogenous subsurface. A mobile configuration was used, whereby the instrument is towed behind a quad bike equipped with a GPS and navigation unit. Survey transects with 2 m spacing were used, with an approximate 0.25 m in-line sampling density. After removing the influence of temporal drift (Hanssens et al. 2021), interpolation to 0.5 m resolution was undertaken. A 1D inversion procedure was also performed using EMagPy (McLachlan et al. 2021) to investigate vertical variations in conductivity and examine differences between the apparent conductivities and modelled 'true' distributions. For this, a cumulative sensitivity forward model was used (following McNeill 1980a).

Limited invasive sampling using boreholes was also undertaken along several transects to record soil profiles and collect samples for further laboratory analysis. An Edelman auger (10 cm diameter) was used at select locations both inside and outside colluvial deposits (according to the existing soil mapping and results of the FDEM surveys). Soil descriptions were recorded for each borehole and at least one bulk sample was taken from each recorded soil horizon. Samples were weighed and oven-dried for 24 hours at 105° C to record gravimetric moisture content. Resistivity of the bulk sample was measured in the lab using a soil box and a resistivity meter with a four-electrode configuration (Miller 400D, M.C. Miller, USA). Texture analysis was then performed on select soil samples using the pipette method (Standard NF X31-107). This analysis provided data on the % of clay (<2 μm), fine silt (2-20 μm), coarse silt (20-50 μm), fine sand (50-200 μm) and coarse sand (0.2-2mm) in each sample.

Results

The classified landforms map based on the geomorphons method is shown in Figure 58. The depositional areas show where colluvial deposits are likely to accumulate with the steep slopes indicating the most erosion-prone areas. Overlaying the mapped colluvial deposits from the existing soil mapping (Louis 1958, 1973) shows a high degree of correspondence (with areas of high erosion risk located immediately adjacent to indicated extents of colluvial deposits), following the typical model of catena development (Schaetzl 2013).

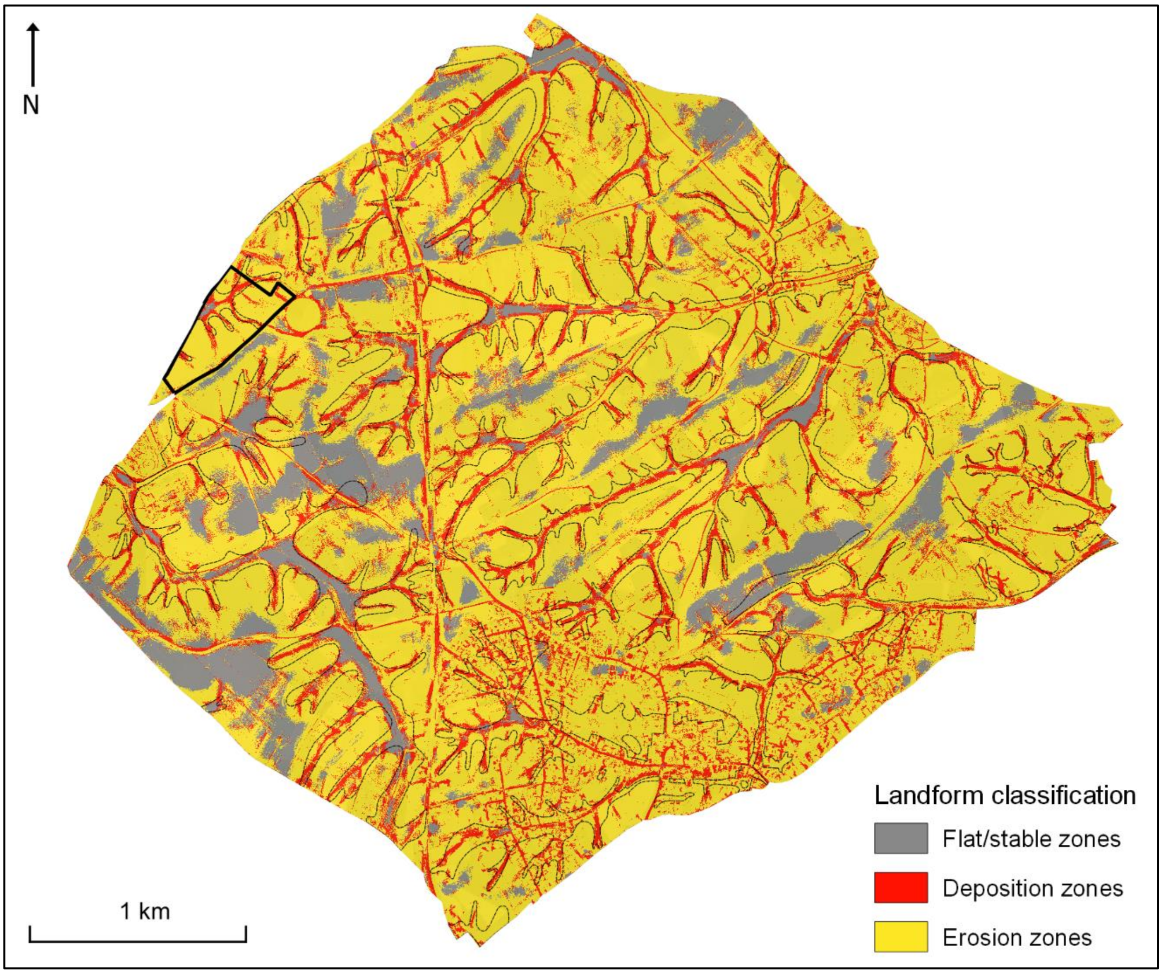

Figure 58: Terrain landforms classified using the geomorphons method for the entire study area. Dotted black lines indicate colluvial deposits mapped during mid-20th century soil surveys. Area A shown in solid black at northwest edge. Figure by author.

Figure 59 compares high-resolution orthophotos from different years for Area A, showing the contrasts that the colluvial deposits and eroded areas present under different conditions. These differing contrasts are due to the environmental conditions at the time the photo was taken (soil moisture, vegetation cover, and phenological stage of crop). It appears that colluvial deposits tend to support greener (i.e., healthier) vegetation and eroded areas between them appear as comparatively bare soil (lighter coloured). While the latter phenomenon is logical and consistent with what has been observed elsewhere (Netopil et al. 2022), the association of vegetation health with colluvial deposits has been less well established in the literature.

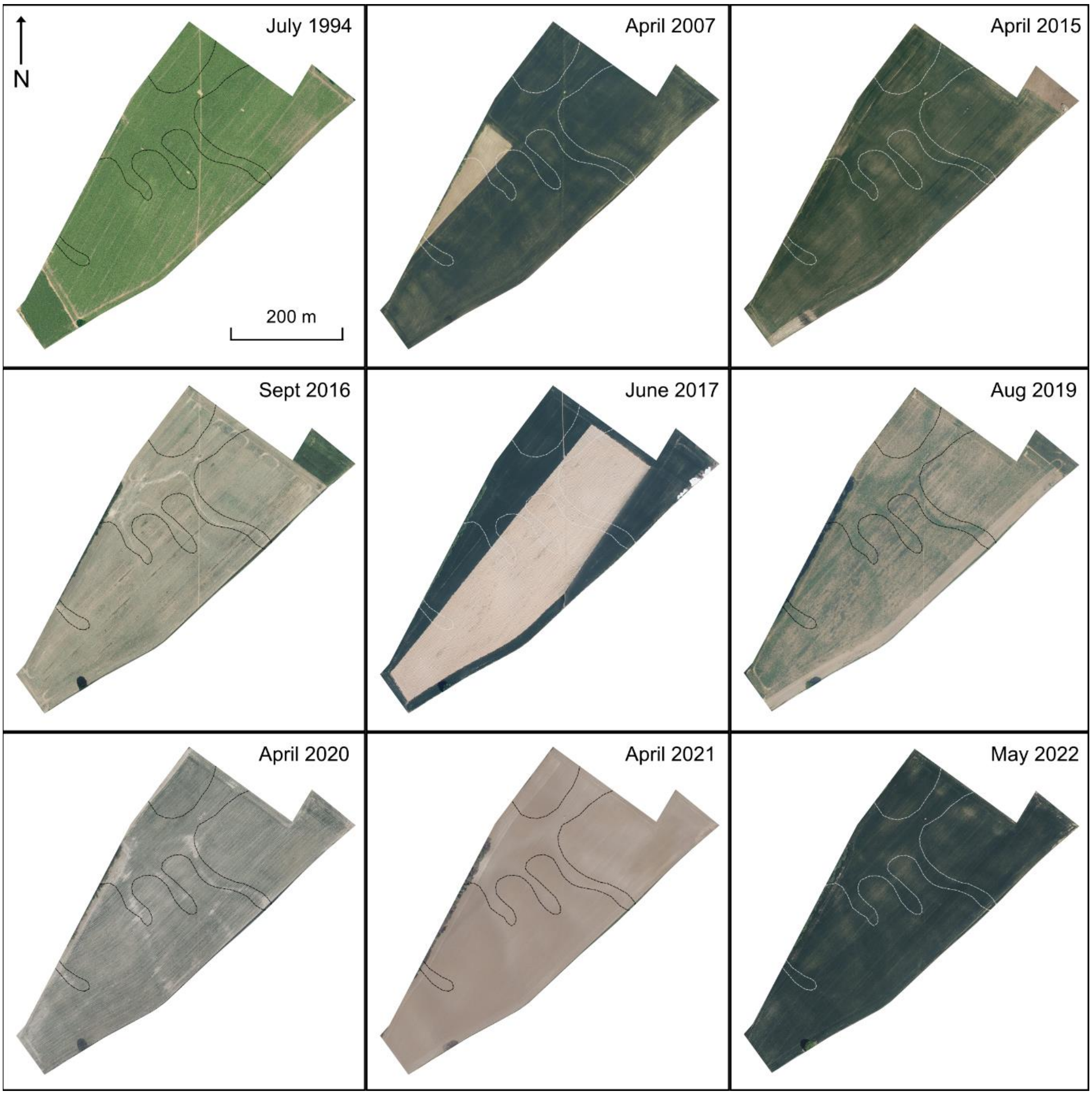

Figure 59: Orthophotos (from Géoportail de la Wallonie) from various years showing varying contrasts of colluvial deposits. Mapped deposits from 1950s soil surveys indicated by dotted lines. Figure by author.

This relationship appears to be valid across large portions of the study area but its year-to-year manifestation is inconsistent. Under relatively bare (low biomass) conditions, for instance, (e.g., 2021) areas of apparently bare soil (appearing brighter) are visible within certain colluvial deposits, with intervening eroded or transitional areas appearing darker. Examination of S2 scenes from approximately the same dates, however, show that vegetation indices are still marginally higher in the colluvial deposits. In other photos (e.g., 2016), distinct (ephemeral) gullies are visible as narrow linear features within larger colluvial deposits, indicating further gully erosion taking place within certain depositional areas. Lastly, there are also examples of photos where no contrast is visible (e.g., 1994).

As previously noted, multi-temporal composites provide a way of overcoming these varying conditions. Figure 60 shows a dry-season bimonthly composite (March-April, May-June, and September-October) of EVI values for the S2 dataset. Lighter-coloured zones in this composite represent higher EVI values. Individual bimonthly composites are also shown in Figure 61. While some of the same patterns are visible in the individual composites (colluvial deposits appearing darker in grayscale, i.e., with higher EVI values), the false-colour visualization demonstrates the benefits of combining multiple composites. Similarly, the EVI image for the entire mean-reduced collection shows contrasts in many of the same areas but appears to show slightly less detail than the bimonthly seasonal visualization.

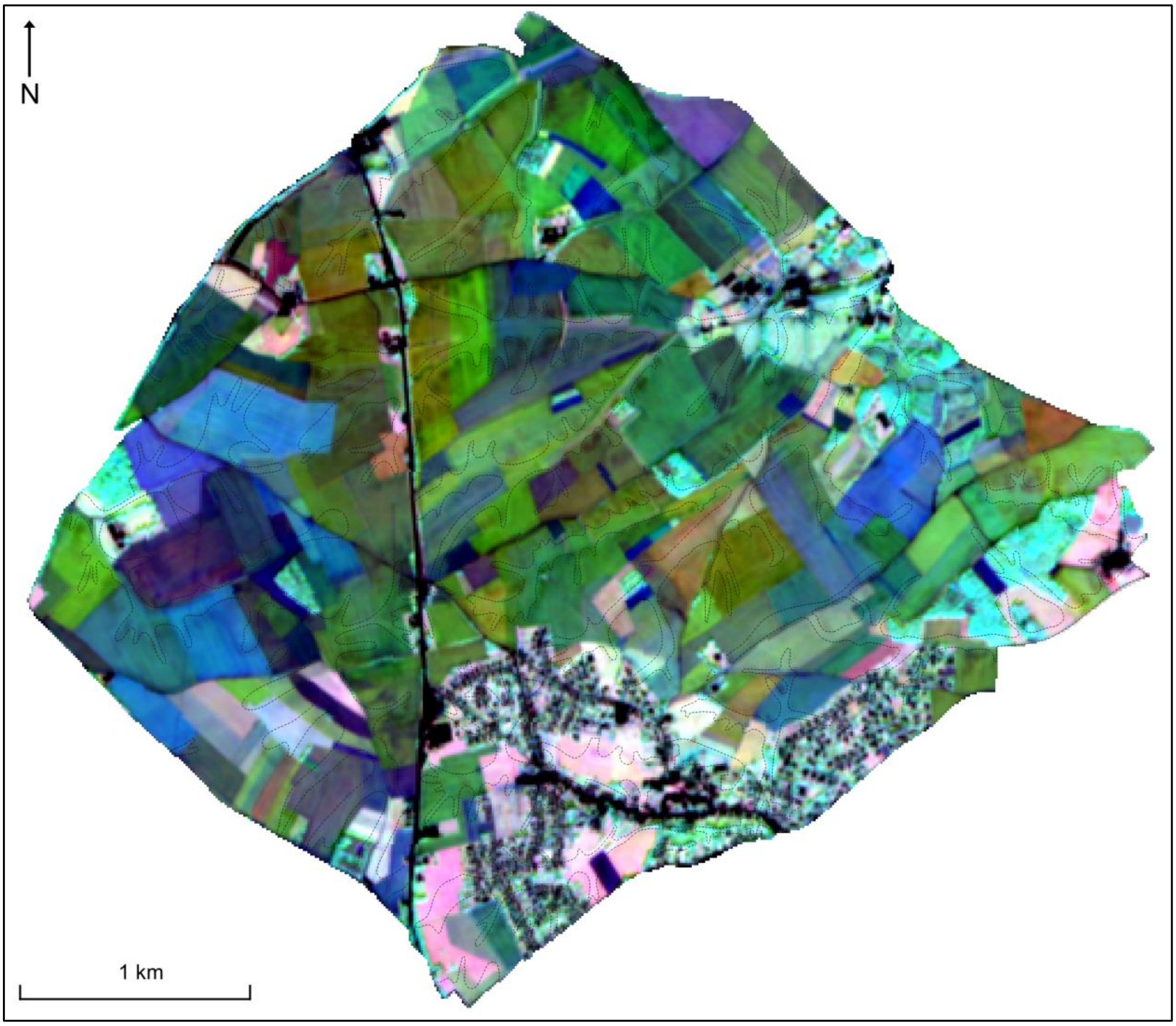

Figure 60: False-colour composite of dry-season EVI from Sentinel-2 data (March-April, May-June, September-October). Figure by author.

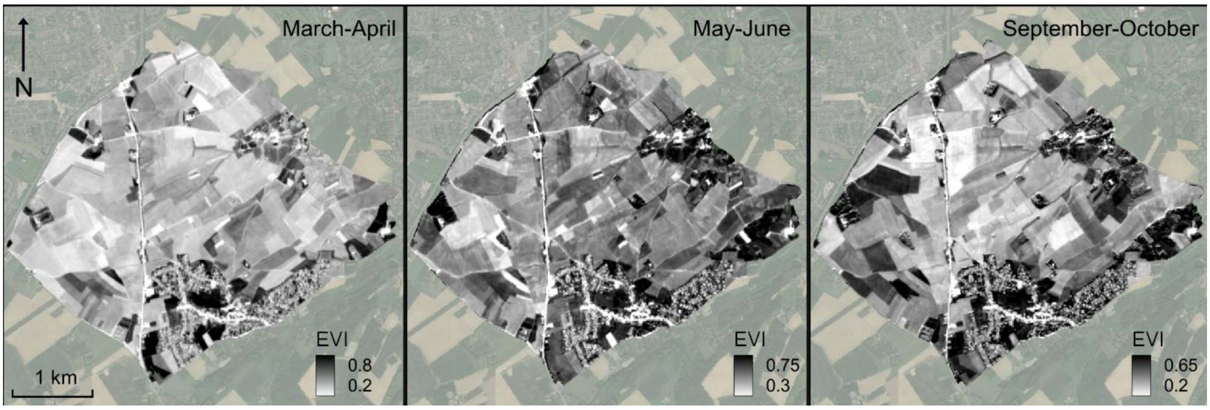

Figure 61: Bimonthly composites making up the false-colour composite in Figure 60. Basemap Google Earth, 2021, figure by author.

A clear correlation is visible between areas with higher EVI values and the colluvial deposits on the existing soil mapping. Greater detail can be seen in the EVI composite (Figure 60), with some additional areas that are not shown on the existing mapping. Comparing the EVI composite with the landform mapping, however, shows very good correspondence. Thus, colluvial deposits clearly show a tendency in this soil environment to support healthier vegetation, as was suggested by the examination of individual air photos above. The exact reasoning for this remains somewhat unclear but is perhaps due to a preferential moisture regime (i.e., more plant-available moisture), which could relate to texture differences (de Jong Van Lier et al. 2023)) and increased organic matter in these areas (Schaetzl 2013, fig. 3; Lal 2020). Despite the visible presence of these patterns, attempts at segmentation of the S2 dataset, using k-means clustering, proved unsuccessful with the colluvial deposits failing to be extracted. Instead, the clustering algorithm identifies the field boundaries as the major contrasts. The contrasts between the colluvial deposits and the soil background are much subtler and thus obscured by other larger variations.

The impact of spatial resolution is clear, however, when comparing the results of the S2 EVI image with an L8 image over the same period (Figure 62). While some of the larger features are still vaguely present, there is a considerable reduction in visibility of within-field variability with the major contrasts being those between fields. Given that many of the mapped colluvial deposits have widths smaller than the Landsat spatial resolution, this is unsurprising. Area A serves as a good example of this, with all mapped deposits in this field having widths of less than 30 m. This suggests that further increasing the resolution of remote sensing datasets beyond the 10 m of the S2 datasets could yield additional insight and indeed this is the case with the orthophotos noted above.

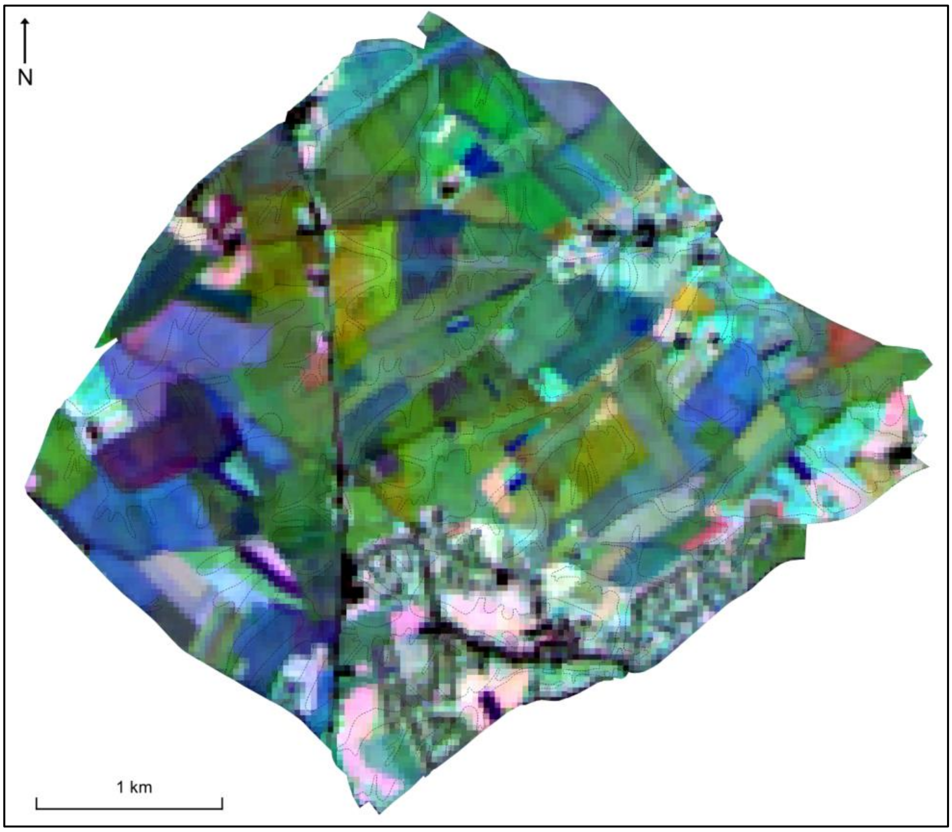

Figure 62: False-colour composite of dry-season EVI from Landsat-8 data (March-April, May-June, September-October). Compare with Figure 60. Figure by author.

Turning to the geophysical data, a map of FDEM apparent electrical conductivity (ECa) for coil pair HCP1 is shown in Figure 63 for the entire study area. The lighter-coloured zones represent areas of lower conductivity (higher resistivity) and correlate strongly with the existing soil mapping of colluvial deposits, although with considerably more detail (partly given the much higher sampling resolution). This is due primarily to the smaller contribution of the clay-rich (i.e., high-conductivity) Bt horizon to the cumulative measured volume in these areas, as it is more deeply buried beneath recently eroded material. At the same time, the colluvial deposits themselves are characterized by coarser soil textures than the Bt horizon found at the same depth outside these zones (see below). Figure 64 shows ECa for each coil pair for Area A; the relative contrasts remain quite consistent across the different coil pairs, although the overall values increase due to the increasing influence of the Bt horizon in the deeper coil pairs. Inverted depth slices for Area (at depths of 0.3 and 1 m, corresponding approximately to the bottom of the ploughzone and the Bt/colluvium interface), also show very similar patterning (Figure 65), indicating that the ECa maps are quite robust for predicting areas of colluvial deposition. Furthermore, a k-means clustering for the ECa data shows that these features can be extracted very effectively, compared to the remote sensing data examined above (Figure 66).

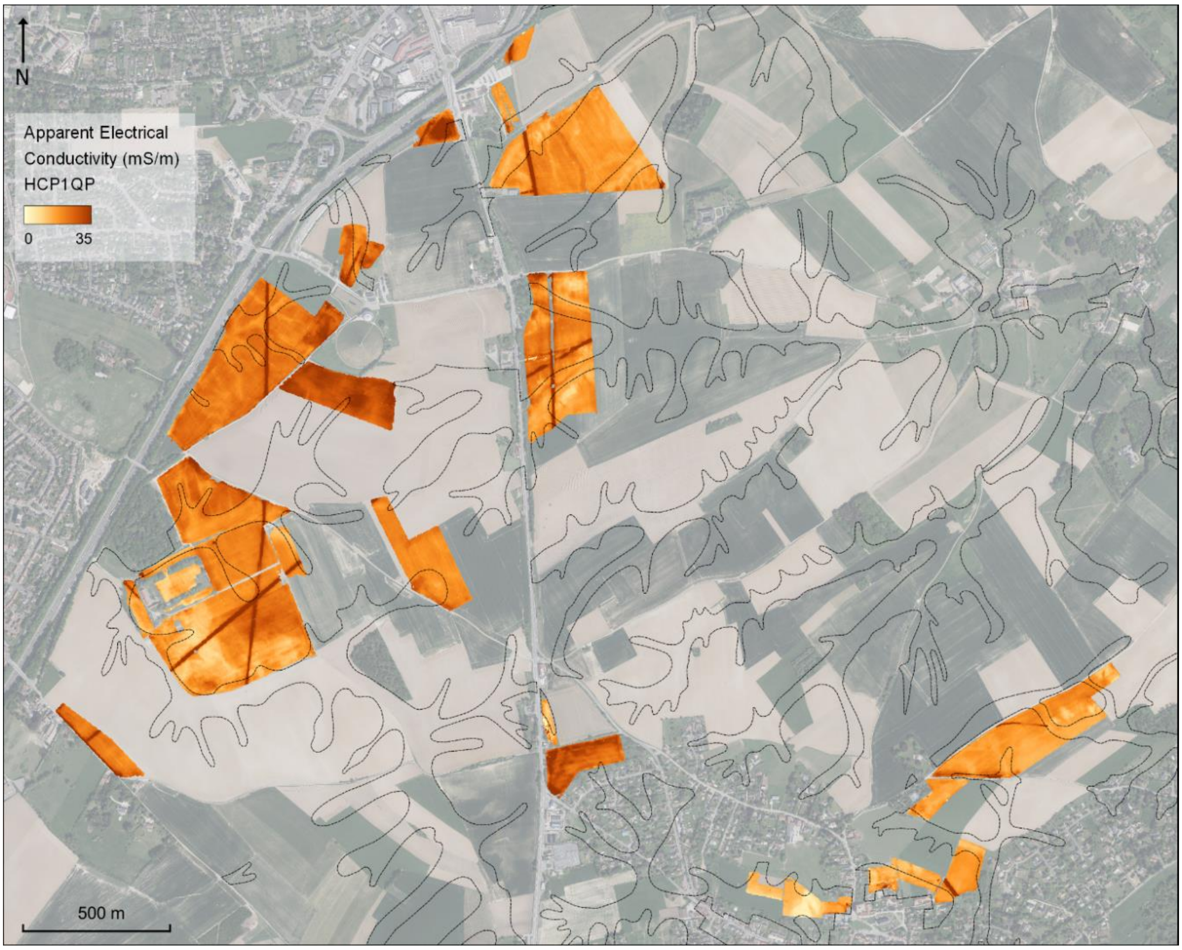

Figure 63: ECa data for coil pair HCP1. Colluvial deposits from 1950s soil surveys indicated by dotted black lines. Air photo basemap from Géoportail de Wallonie (2022). Figure by author.

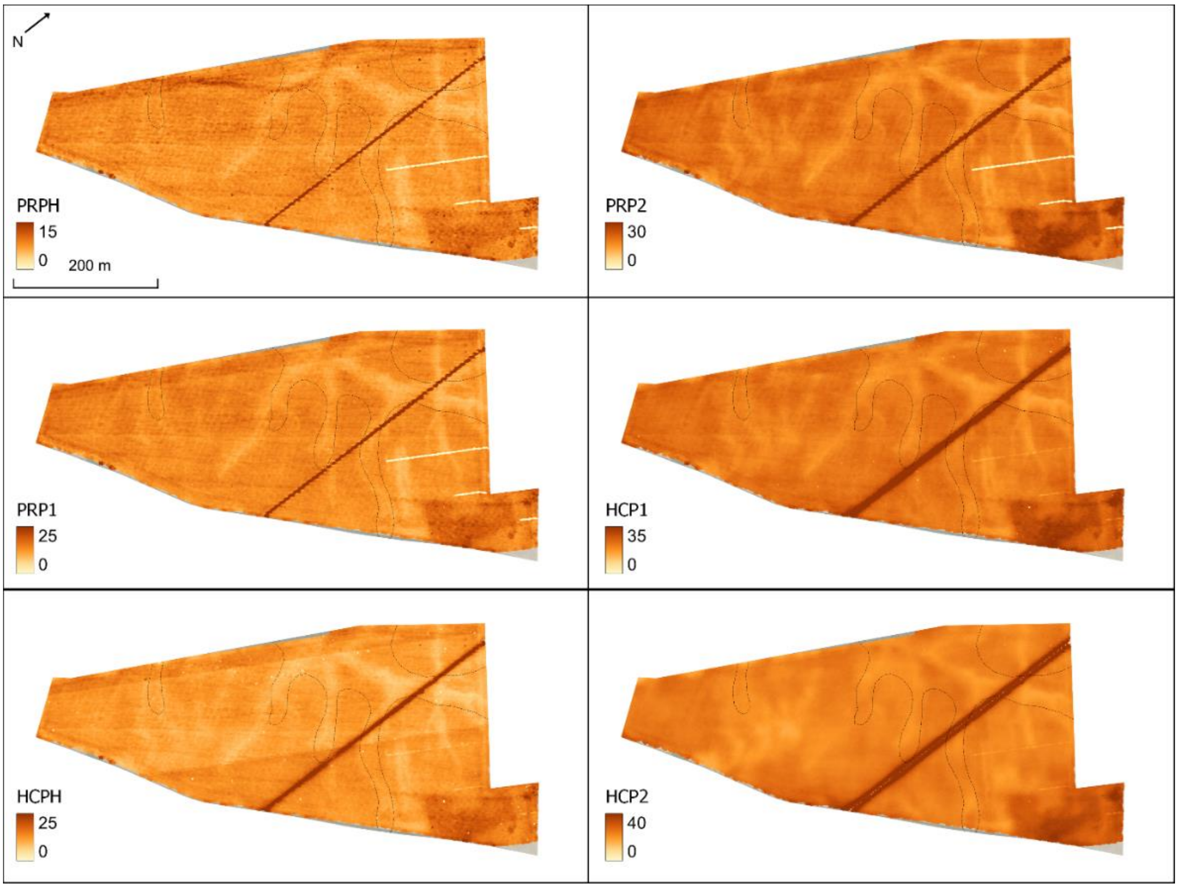

Figure 64: Apparent electrical conductivity for each coil pair for Area A. Figures by author.

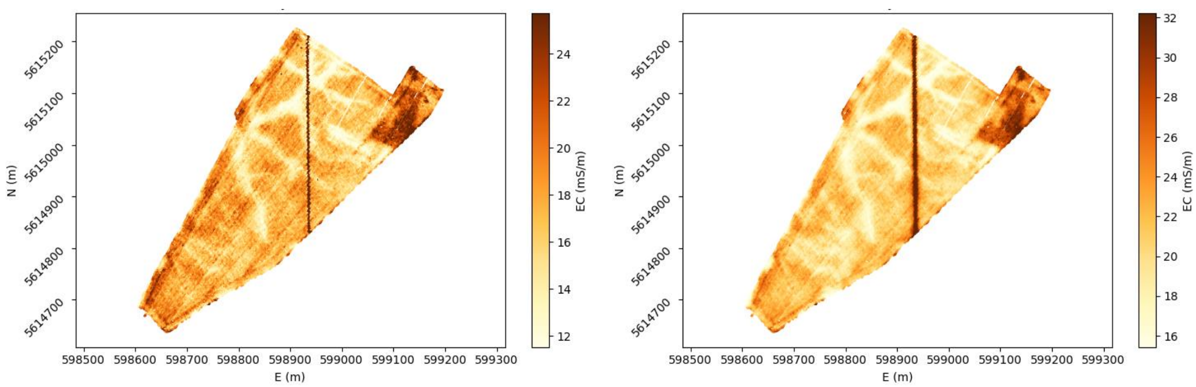

Figure 65: Inverted conductivity slices at depths of 30 cm (left) and 1 m (right). Figures by author.

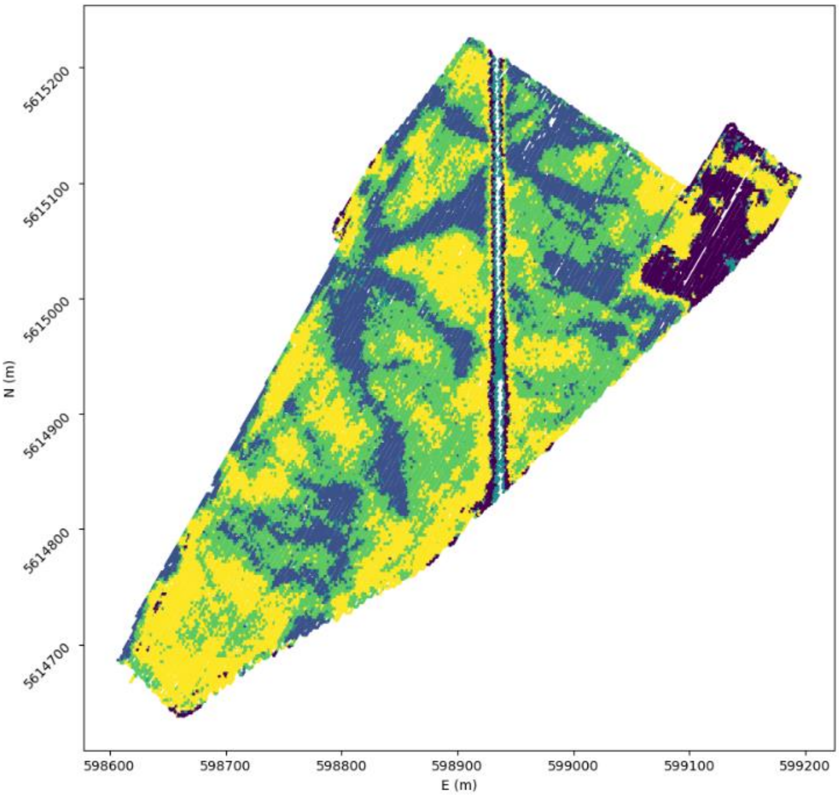

Figure 66: Results of k-means clustering of HCP1 apparent conductivity (5 clusters). Blue cluster corresponds to colluvial deposits. Figure by author.

Figure 67 summarizes the terrain modelling, remote sensing and geophysical datasets for Area A and shows the location of a reference transect.

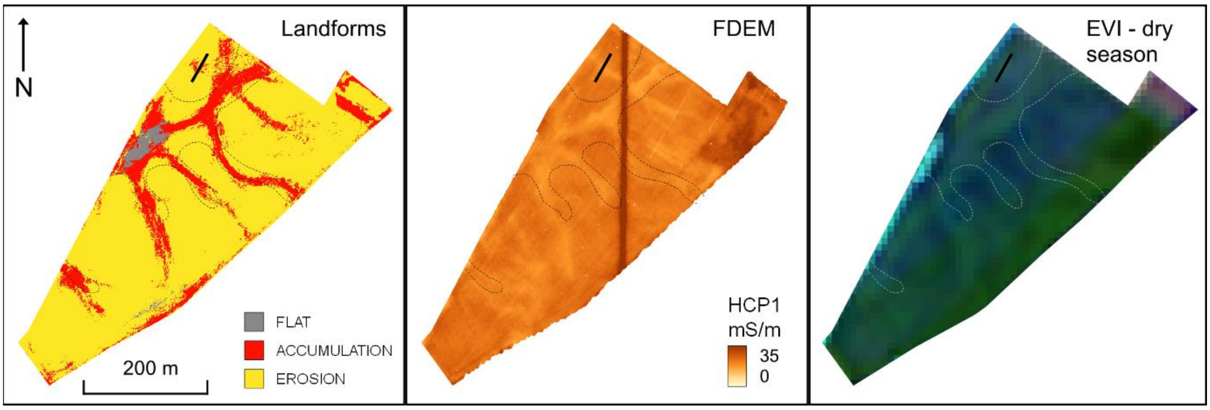

Figure 67: Terrain modelling, (apparent) electrical conductivity, and Sentinel-2 EVI composite for Area A. The location of the reference transect described below is indicated by the solid line at the northern end of the parcel. Figures by author.

Figure 68 shows an inverted conductivity profile from the FDEM dataset for a reference transect through a colluvial deposit in Area A. The deposit is clearly visible in the lateral ECa data as an area of low conductivity, although it is not mapped as a colluvial deposit in the existing soils data. Terrain modelling indicates that a small portion of the transect crosses through a depositional area but that it is not as well-defined as other depositional areas in the parcel. It is also visible as an area of elevated EVI in the S2 data. The inverted profile very clearly shows a low-conductivity zone in the centre of the profile with a highly conductive layer at the same depth on either side of it.

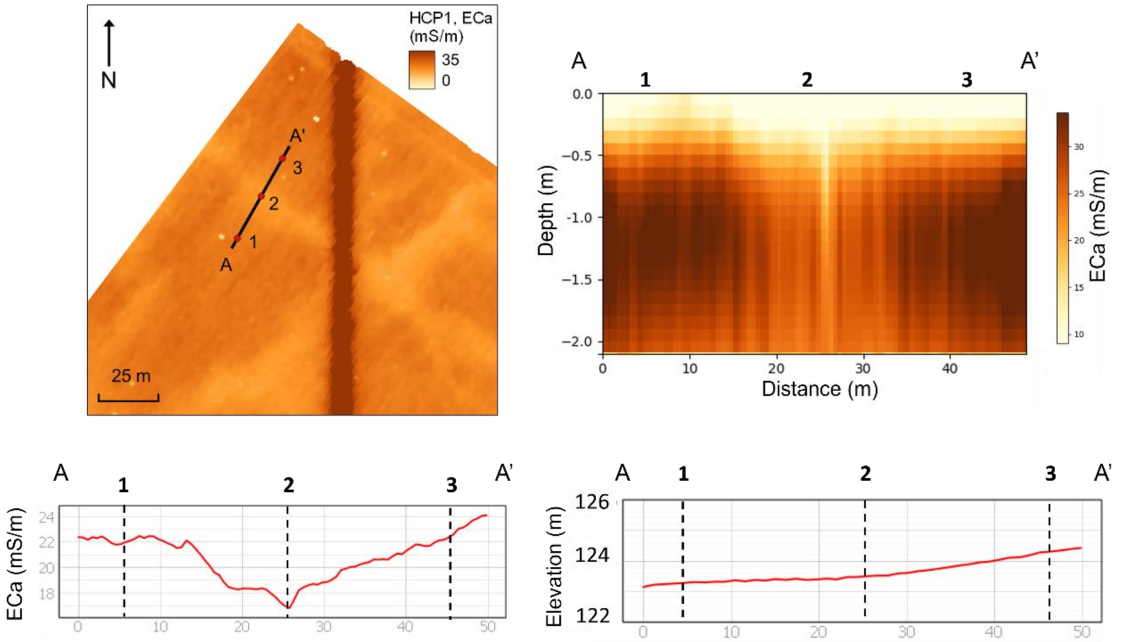

Figure 68: Reference transect in Area A. Location of transect and boreholes shown top left, inverted profile top right with borehole locations. ECa values (HCP1) and elevation across the transect shown on bottom left and right with borehole locations indicated. Figures by author.

Three boreholes were placed along the transect: one in the centre of the low-conductivity feature and one on either side of it. These confirmed the variable depth of the Bt horizon, with the layer being found at a shallower depth outside the feature (at 0.3 m depth, extending to approximately 1 m) and beneath colluvial overburden in the centre of the feature (appearing at 1.1 m depth and extending to nearly 2 m) (Figure 69).

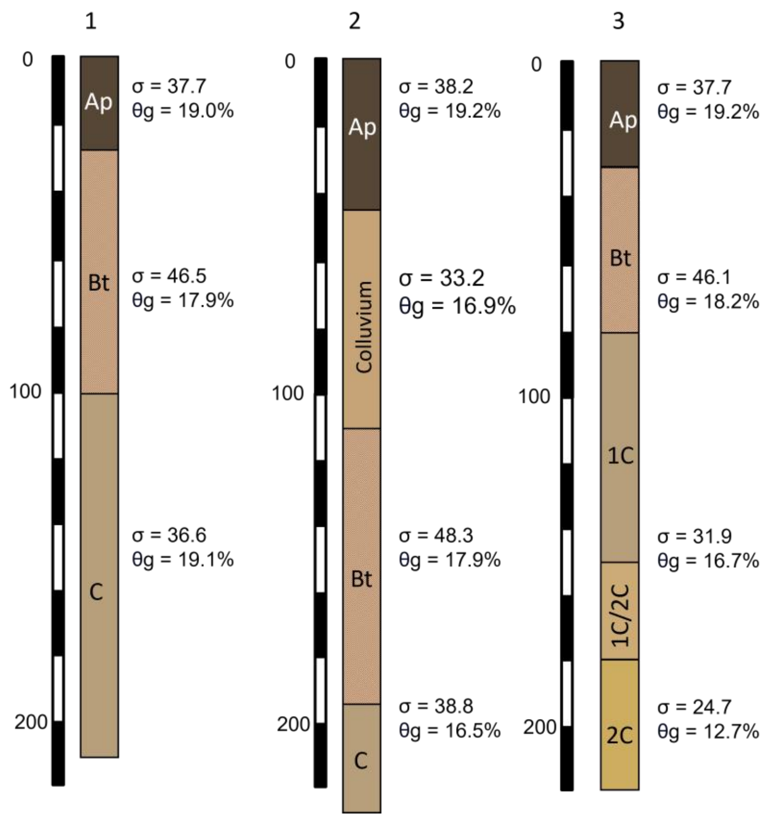

Figure 69: Soil profiles for boreholes along transect, with conductivity (σ) and gravimetric moisture (θg) of collected samples indicated. Figures by author.

Lab (soil box) resistivity measurements (shown in Figure 69) confirmed the increased conductivity of the clayey Bt horizon and lower conductivity of the colluvium. The ploughzone was found to be quite homogenous with nearly identical conductivity across the three boreholes. Moisture content was variable but the overall range is minimal and does not appear to be strongly correlated with conductivity or soil horizon. Results of soil texture analysis confirm that the increased clay content in the Bt horizon is responsible for the higher conductivity of this layer (Table 4). While all samples were classified as silty loam, the Bt samples have notably elevated clay content and comparatively less fine sand, whereas the colluvial sample is characterized by the opposite. This indicates that soil texture clearly plays an important role in the formation of colluvial deposits. The increase in fine sands is consistent with the findings of other researchers, who report that these soil textures in particular have high erodibility (French 2016, p. 157).

Table 4: Soil properties for samples from boreholes along Transect 2, Area A. The results for the texture analysis for the colluvium and Bt horizons also correspond very closely to values reported by Louis (1973).

Borehole	**Depth (cm)**	**Soil horizon**	**Organic matter (%)**	**Clay (%)**	**Fine silt (%)**	**Coarse silt (%)**	**Fine sand (%)**	**Coarse sand (%)**	**Moisture (%)**	**Conductivity (mS/m)**
1	75	Bt	0.13	21.9	33.4	40.9	3.7	0.1	17.9	46.5
2	25	Ap	1.11	17.2	25.9	46.9	8.6	1.4	19.2	38.2
2	75	Colluvium	0.28	16.8	22.5	48.3	11.2	1.2	16.9	33.2
2	150	Bt	0.12	21.9	26.7	46.1	5.1	0.1	17.9	48.3
2	200	C	0.08	18.8	24.7	49.9	6.4	0.2	16.5	38.8
3	200	2C	0	12.7	14.3	65.6	7.2	0.2	12.7	24.7

Profiles of inverted conductivity for the borehole locations along this transect are shown in Figure 70. The different shapes allow for clear differentiation of the colluvial deposit: the boreholes outside the deposit both have similar horizontal parabolic shapes, reaching a maximum value at a depth that corresponds approximately to the Bt-C horizon transition, while the one inside the colluvial deposit has a less pronounced curve, a deeper maximum, and a more gradual decrease further down the profile. The decreasing conductivity seen in all profiles is due to the underlying sandy Tertiary substrate, also clearly reflected in the texture data (Table 4).

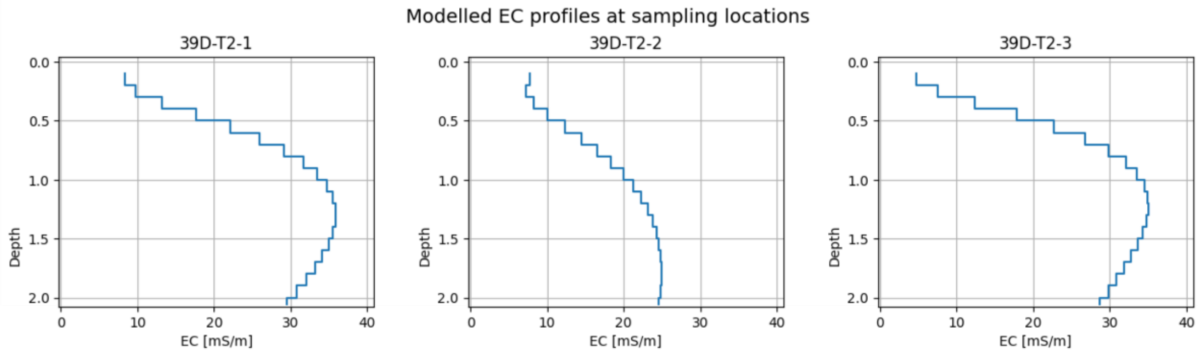

Figure 70: Inverted conductivity profiles for boreholes along reference transect. Figures by author.

Another example demonstrates the archaeological relevance of this exercise by illustrating a transect through a previously unmapped zone of colluvium overlying an archaeological feature dating to around the time of the battle (Figure 71). The inverted profile shows a relatively well-defined (but undulating) lower-conductivity zone in the centre of the profile between approximately 20 and 80 m. It is visible in plan as a diffuse zone on the ECa data but is not recognizable in the S2 EVI data. A magnetic anomaly was mapped in FDEM and FM surveys and revealed to be the remains of a forge deposit at a depth of approximately 0.7 m. Despite containing large quantities of ferrous material and having a magnetic susceptibility of more than 100x that of the surrounding soils, conventional metal detecting did not render a signal from the surface.

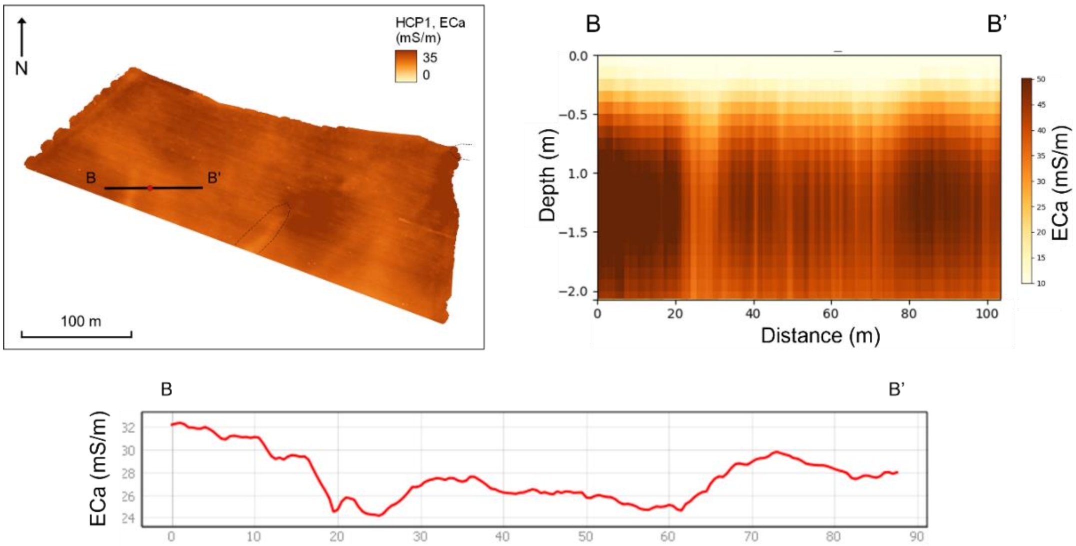

Figure 71: Location of transect over colluvial deposit and archaeological feature (indicated by red dot) on left. Inverted conductivity profile on right. The archaeological feature (also shown in Figure 56D) is located at about 40m along the profile, in the lower-conductivity zone. Figures by author.

Lastly, it is interesting to consider the expressions of colluvial deposits in other geophysical datasets from the study area. The IP component of the FDEM data, representing MSa, correlates very well with the ECa data and also allows for the delineation of many colluvial deposits (Figure 72). These are visible as broad zones of enhanced magnetic susceptibility. This likely relates to the thicker topsoil/ploughzone horizons present in these areas, which characteristically have higher magnetic susceptibility (Fassbinder 2015). These patterns were not apparent in fluxgate magnetometry surveys of the same areas, likely due to the influence of the gradiometer configuration which inherently acts as a high-pass filter removing low-frequency variations.

Figure 72: MSa data for coil pair HCP1. Colluvial deposits from 1950s soil surveys (Louis 1958, 1973) indicated by dotted black lines. Air photo basemap from Géoportail de Wallonie (2022). Figure by author.

GPR profiles performed over colluvial deposits also failed to render any visible contrasts, suggesting that permittivity does not differ significantly down the profile, which is also reflected in the moisture data derived from collected samples (see Table 4). While GPR has been suggested as a potential method (French 2016, p. 165) and effectively used elsewhere for mapping colluvial deposits (in particular those that are heterogenous and unconsolidated) (Gerber et al. 2010; Fernández-Álvarez et al. 2016), the more homogenous soil conditions encountered here proved unsuitable. It should be noted that issues with ground coupling and attenuation, as noted in Chapter 4, are also partly responsible for this.

Finally, a 2D ERT survey was performed over the reference transect shown in Figure 68 and showed the same contrasts observed in the FDEM surveys (Figure 73). Equipment issues resulting in an incomplete dataset prevented the full inversion and quantitative analysis of this data and it was thus not considered further. The persistence of the same electrical contrasts in different seasons (the FDEM surveys were performed in Autumn 2022 and the ERT measurements in Spring 2023), however, is notable given the often seasonal nature of these contrasts in soil environments. This indicates that there is potential for the use of ERT profiling for the purposes of mapping colluvial deposits. While the FDEM inversions outlined above were highly successful, this may allow for increased resolution and sensitivity.

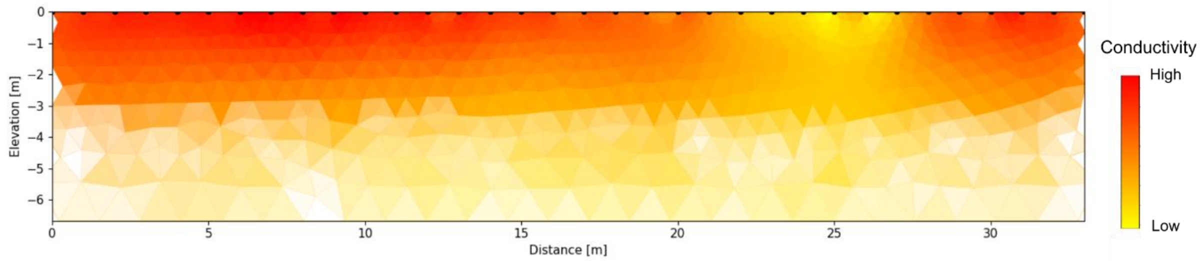

Figure 73: ERT profile conducted over reference transect shown in Figure 68 (displayed in conductivity). Colluvial deposit clearly visible as low-conductivity feature between ~22-27 m. Data only shown qualitatively due to incomplete inversion. Figure by author.

Discussion

The preceding section shows how complementary methods can be integrated across different spatial scales to provide insight into the presence and extent of colluvial deposits in a loess soil environment. The remote sensing and terrain modelling approaches are most useful at the landscape scale. Geophysical survey provides a higher-resolution field-scale perspective and allows for a more detailed examination of the subsurface. Targeted invasive sampling, combined with analysis of relevant soil properties, allows for a more robust understanding of sensor data and refinement of interpretations. The combination of these methods allows for bridging gaps between discontinuous and labour-intensive field sampling and large-scale modelling approaches lacking the local resolution required for detailed mapping.

The terrain modelling sought to define three main landforms: erosion-prone areas, depositional zones, and intermediary stable areas. It is suggested that using topography for defining erosional features is a robust approach in this case, given the homogeneity of other factors influencing erosion (rainfall erositivity, soil erodibility, vegetation cover, and landuse/support practices) at the scale of the study area. This approach, however, does not allow for the direct identification of colluvial deposits or even associated proxies, relying instead on terrain as a covariate.

Recognizing the role of vegetation health as a proxy for the location of colluvial deposits in the study area, based on high-resolution orthophotos, vegetation indices were extracted from multi-temporal collections of multispectral remote sensing data. Whereas many researchers have used vegetation indices in erosion modelling approaches and have used the presence of higher indices (healthier vegetation) to infer a diminished risk of erosion (e.g., Ayalew et al. 2020), the association of vegetation and colluvial deposits has been less commonly employed. The homogeneity of the soil environment in the study area allows for the recognition of subtle relevant contrasts in the remote sensing data. This complicates the (semi-) automated classification of the dataset, however, given the relative weight of other contrasts. Thus, the remote sensing approach is limited by landuse constraints which mask more fine-grained variation. A multi-temporal approach for examining long-term trends provides one solution to this variability but also introduces a level of additional noise through the aggregation of different images under different conditions. Fine-tuning of image selection and identifying ideal moments when contrasts are most evident (e.g., in periods of particularly high rain erositivity (Verstraeten, Poesen, Demarée, et al. 2006)) may assist in developing more robust composite datasets. This is particularly important with regards to higher-resolution imagery with less frequent revisit times.

The impact of spatial resolution was clearly demonstrated with the comparison of Landsat and Sentinel imagery, and the latter is still rather coarse for the identification of small features. Other remote sensing methods not examined here may also prove useful for identifying contrasts. In particular, sensors targeting soil moisture such as RADAR platforms (Jensen 2014, chap. 9) or possibly LiDAR intensity (Challis et al. 2011; Garroway et al. 2011) may prove effective, though these are also impacted by factors such as vegetation cover. The former has the advantage of high temporal resolution but typically lower spatial resolution while the inverse is true for the latter.

Due to the homogeneity of the soil environment and subtle nature of the contrasts, combined with the small scale of the features of interest, geophysical methods were employed for the higher-resolution mapping of soil properties. Measurement of (electrical) soil properties and their subsurface variation enabled relatively straightforward identification of colluvial deposits. This was accomplished largely by mapping soil texture variability, using conductivity as a proxy. Here, depth to the clay-rich Bt horizon is used as a proxy for the thickness of the colluvial overburden. Variations in soil texture, though still quite subtle, were clearly observable and confirmed by sampling and laboratory analyses. The 1D inversion of FDEM data provides further insight into the vertical variation of conductivity and thus the depths of soil horizons of interest. Inverted profiles can be examined in a qualitative manner to rapidly gain insight into the presence and extent of colluvial deposits. The inverted data correlates very well with field and laboratory observations of selected borehole samples, which is extremely promising for the interpretation of sensor data in this environment. Additional sampling could allow for the calibration of a quantitative model for predicting depths of relevant deposits (topsoil, colluvium, clay-rich Bt, and sandy substrate), a possibility which was not explored here. The same electrical patterns were shown to persist in a dataset collected with a different technique (ERT) and during a different season. Examination of the in-phase (magnetic susceptibility) component of the FDEM data also showed the same broad patterns as the ECa data, though the IP data are less sensitive and result in a coarser mapping.

It should be noted that, while observed patterns in the ECa were largely consistent across the study area, the exact contrasts will be dependent on the specific pedological properties of the parent material. For instance, in one parcel at Waterloo, the impact of a sandier substrate causes a reversal of the observed patterns, such that colluvial deposits actually present as more conductive features. In these areas, the thinner loess cover (and clay-rich Bt) exerts less of an influence on the bulk conductivity with an increased contribution from the sandy Tertiary substrate. This is the case for the quarry pit feature described in Chapter 4 (Figure 49), where the fill of the feature is more conductive than the surrounding soil. Other colluvial deposits in the same parcel also showed the same trend. Thus, a contrast (again largely on the basis of texture) persists but is influenced by the specific soil environment. Other studies have shown that, even in a ploughzone, textural differences can be directly correlated to slope position and that these are related to erosional factors rather than pedogenesis (Malo et al. 1974). While the ploughzone samples examined at Waterloo appear to be largely homogenous in terms of soil texture, this further demonstrates the important effect of texture sorting in water erosion.

A more detailed understanding of the distribution of colluvium at the site is archaeologically relevant for several reasons. First, it dictates the depth of archaeological deposits of interest and thus informs sampling strategies. Standard prospection methods may be ineffective in some cases and techniques specifically aimed at deeply buried deposits may need to be considered, ranging from mechanical excavation to more novel geoarchaeological sampling approaches (e.g., Missiaen et al. 2015). Geophysical survey should still be effective in most cases, though may require some additional consideration of particular instrument choice and configuration (e.g. magnetometry in total-field, rather than gradiometer mode) (Kvamme 2006; Crabb et al. 2022).

Secondly, for battlefield archaeology in particular, this has important implications as the effectiveness of relied-upon conventional metal detection may be severely hampered in certain areas. The assumption here is that objects originally deposited in certain areas will subsequently be covered over by eroded sediment and become undetectable. This is, however, not a straightforward assumption and is complicated by other factors, primarily the impact of ploughing on the distribution of material in the topsoil (Yorston et al. 1990; Boismier 1997). There is also the strong possibility that downslope movement of some material will have occurred as part of the erosion process, as been observed in many archaeological contexts (Smith 2001; Collins et al. 2016; McCoy 2021), although this should not be a universal assumption (James et al. 1994). In some cases, it has been documented that denser/heavier objects will be more susceptible to this kind of downslope movement, though the additional influences of fluvial erosion further complicate this (Rick 1976). For Waterloo specifically, and for battlefield contexts more generally, this is still poorly understood, but the detailed mapping of sedimentary contexts as examined here provides an important starting point. The spatial integrity of artefact distributions is a particularly important consideration for battlefield archaeology; in many cases, artefact scatters are all that remains of a conflict site and their spatial distribution thus has a great deal of interpretational value (Banks 2020). Identifying biases in the dataset is thus a fundamental exercise.

While the deep burial of archaeological deposits can be seen as a negative as far as the use of certain prospection methods, it is also a positive from the point of view of preservation (e.g., Bosquet et al. 2015). Thus, contexts sealed beneath colluvial overburden are less likely to be subject to plough damage, further erosion, bioturbation, etc. Conversely, those which existed in areas sensitive to erosion are more likely to have been destroyed. This is particularly relevant for the types of features related to battlefields, which tend to be very ephemeral.

A major limitation of the present study is that robust chronological information is missing, thereby preventing a reconstruction of the sedimentation sequence in depositional areas of interest. Coarse relative dating is possible in cases where datable archaeological contexts are found beneath colluvial deposits, providing a *terminus post quem* for the overlying sediments. This is only possible, however, for *in situ* archaeological remains; using artefacts for the relative dating of colluvial deposits is less reliable given the possibility of mixed or inverted stratigraphy (French 2016, p. 166).

In the case of Waterloo, the assumption that the majority of colluvial deposits are relatively recent (i.e., since the time of the battle) is probably valid. This is particularly related to the influence of mechanized ploughing in the last half-century. It is also likely that the enlargement of field parcels during the same period has played a role, resulting in a reduction of field boundaries which act as deterrents against erosion; this phenomenon has been demonstrated to have increased the risk of water erosion elsewhere in the Belgian loess belt (Van Oost et al. 2000, pp. 583–584). The phenomenon of greatly increased recent erosion at Waterloo is also supported by other long-term chronological studies of colluvial sequences in western Europe, some of which have shown that the majority of colluvial sediments derive from the past couple hundred years (e.g., Kappler et al. 2018). It may be possible to gain further insight into historical rates of erosion through a change detection approach, examining archive aerial photos to assess distributions of eroded areas (e.g., Jenčo et al. 2020; Netopil et al. 2022).

Aside from relative dating, there are several other methods that have potential for a more refined understanding of the chronology of sedimentary sequences at Waterloo. One is optically-stimulated luminescence (OSL), which has been widely applied to the dating of sediments in various contexts (Rhodes 2011), including colluvial sediments (Fuchs and Lang 2009; Lang 2015), and has a long history of archaeological applications (Duller 2008). The technique relies upon the measurement of stored energy in certain minerals (especially quartz), which is acquired via environmental radiation and resets upon exposure to light (Aitken 1998). It can be used to determine the last exposure date of a sample (and thus the date at which it was buried). The datable period can be as short as a single year up to hundreds of thousands of years (Rhodes 2011). In its traditional lab-based form, OSL allows for the calculation of an absolute date but is quite an expensive process requiring meticulous sampling procedures. Recent development of portable/rapid OSL readers has enabled the measurement of luminescence intensities on bulk unprocessed samples (e.g., soil profiles) (Sanderson and Murphy 2010; Munyikwa et al. 2021). While not allowing for the generation of an absolute age, this provides a proxy measurement for age which can be used to examine variability in a profile and between sampling locations. In this way, it is often frequently used as a screening method to select samples for conventional OSL dating (e.g., Vervust et al. 2020). If a close correlation can then be found between relative field readings and absolute lab determinations, it may even be possible to derive a fitting equation to convert field readings to dates (e.g., Porat et al. 2019).

Another method which has shown great utility for dating of erosion sequences (and in particular more recent ones) is the analysis of fallout isotopes (cesium and plutonium) related to nuclear explosions (Wilkinson et al. 2006; Huisman et al. 2019). These isotopes are not naturally occurring and were released into the atmosphere as fission products. The displacement of soils over the past half-century has disrupted their original uniform distribution. Thus, in stable soil profiles, there is a decrease in concentration down the profile. Eroded areas show relatively lower concentrations, while depositional zones have higher concentrations. A related application is the use of phosphorus content, which relates to the introduction of chemical fertilizers in the early 20th century. Using the same principle as the isotopic tracers, it has been shown that the analysis of phosphorus levels in soil profiles can be used to estimate recent sedimentation rates, although the method is less robust (Steegen, Govers, Beuselinck, et al. 2000).

Conclusion

Alongside impacts to other ecosystem services, soil erosion represents a critical ongoing threat to archaeological resources around the world, particularly in arable landscapes. In addition to monitoring and predicting future erosion rates for the purposes of site management, the reconstruction of sedimentary deposition at a site is a crucial step in the selection of appropriate sampling approaches and interpretation of archaeological data. Thus, the mapping of areas containing eroded sediments (colluvium) is an important objective. While existing mapping products from regional soil surveys typically include some information on colluvial deposits, it is often desirable to gain a more detailed understanding of the lateral extent and depth of these deposits. A multi-scalar approach to mapping colluvial deposits was introduced, which integrates several non-invasive datasets: terrain derivatives to extract erosional and depositional landforms, optical remote sensing for determining vegetation health, and near-surface geophysics for characterizing soil properties. Informed by targeted invasive sampling and laboratory analysis of soil properties, this procedure allows for the detailed mapping and verification of the extent and depth of colluvial deposits.

The approach is demonstrated using a case study examining the Napoleonic battlefield of Waterloo, Belgium situated in a loess environment particularly prone to soil erosion by water. With this framework in place, sampling approaches can be developed to target deposits in areas with increased overburden having higher chances of preservation. This also allows for a better understanding of site formation processes, potential preservation biases, and interpretation of archaeological data via the association of artefacts and features with different sedimentary units. Important next steps include the development of a more robust chronological framework to relate colluvial deposits to archaeological layers of interest; at present, this is only known through relative dating via the association of sealed archaeological deposits with overlying sediments.

Chapter 6 – Summary Discussion and Conclusions

The refinement of methodological approaches has been a continual focus of practitioners of battlefield archaeology, and a contribution in this area was the primary concern of this thesis. Specifically, the greatest challenge is at the prospection level, i.e., in the initial identification of objects and features of interest. Thus, the broad aim of this research has been to examine the application of large-scale prospection methods to the archaeology of early modern conflict sites. The main research hypothesis is that geophysical survey is the most applicable prospection method for this. Important developments in near-surface geophysical methods for archaeological prospection in recent decades have greatly expanded the scale of application (Trinks 2015). While such large-scale surveys have been undertaken with considerable success at a variety of prehistoric (Darvill et al. 2013; De Smedt et al. 2022), classical (Gugl et al. 2021), and medieval sites (Filzwieser et al. 2017), dedicated geophysical surveys on battlefield sites have been comparatively rare (particularly true for those pre-dating the 20th century).

To further explore this potential, the battlefield of Waterloo was used as a case study. An ongoing archaeological project provided an excellent complementary research framework within which geophysical surveys were conducted. The work undertaken for this thesis, involving the collection of over 150 ha of fluxgate magnetometry and frequency-domain electromagnetic induction data, represents the largest geophysical survey undertaken on a single battlefield site. To address the broad aim of the thesis, a series of research questions and objectives were articulated. Individual chapters of this thesis addressed these in turn, and they are recapitulated and summarized below. The chapter concludes with overall perspectives and suggestions for future work.

Assessing the Research Questions

1. What is the potential of near-surface geophysical prospection for early modern battlefield archaeology?

Addressing this question provided the framework for subsequent data collection and allowed for consideration of the chosen approach in relation to other archaeological methods and adjacent disciplines. This topic addressed two overarching and related aims, as outlined in Chapter 2. The first concerned the definition of archaeological targets expected on a typical early modern battlefield site. The focus here was on sites from the gunpowder/early modern period, spanning roughly the 17th-19th centuries, the category to which the main case study of Waterloo belongs. While a selection of case studies from sites pre- and post-dating this timeframe were also considered, significant changes in the strategy and technology of warfare result in decidedly different archaeological signatures for different periods of conflict. In reviewing the literature, it was found that the question of defining the archaeological signature of a battlefield has seldom been addressed in a systematic fashion and is typically treated instead in an implicit or inductive manner, outside of a few exceptions (Harrington 2005; Sutherland 2005; Homann 2013).

The following broad mutually exclusive categories of evidence were defined, each containing more specific subsets: metal objects, burials, field fortifications, encampments, key terrain (anthropogenic landscape), and environmental factors. While this conceptualization is hardly novel, it provides a much-needed systematic overview. With this set of targets defined, consideration was then given to methodological approaches. The broad potential of geophysical survey was presented as a means of bridging the gap between the excellent results of conventional metal detection surveys and the difficulty of identifying other archaeological remains with this approach and other standard prospection methods. It should be noted that not all battlefield sites will have the full range of described targets; nevertheless, unexpected insights may still be gained by the application of geophysical survey.

The second more critical aim was the consideration of geophysical properties associated with each category of evidence that would theoretically enable their identification. This represents an important contribution and a gap in the present literature on battlefield archaeology. Indeed, such a conceptualization is rarely explicitly considered in archaeological prospection more broadly but is an important step in the selection of appropriate techniques and assessment of the effectiveness of a survey. A broad overview of common geophysical methods was given along with a consideration of their potential for particular battlefield targets of interest. The choice of instrumentation is then dictated by the expected targets in combination with the environmental/pedological conditions.

This review reiterated the longstanding methodological challenges faced by battlefield archaeologists and emphasized the potential of large-scale geophysical survey in mediating some of these challenges. It also demonstrated that these challenges are not wholly unique to battlefield archaeology and are critical issues in archaeological prospection more broadly, particularly where ephemeral traces are sought (e.g., Verhegge et al. 2021).

2. How has large-scale geophysical survey contributed to archaeological research at the battlefield of Waterloo?

The battlefield of Waterloo was used as a case study for testing select geophysical methods in large-scale surveys. Specific research questions at Waterloo relate to the curious lack of human remains and evidence for disposal of the dead/battlefield cleanup (Pollard 2021; Wilkin et al. 2023), the degree of integrity remaining in the buried metal finds assemblages in light of decades of intensive and illicit detection (Waterloo Uncovered 2015a), the accuracy of contemporary maps (Waterloo Uncovered 2016), and the impact of soil erosion (Eve 2021). Many of these questions were approached through archaeological excavations at Hougoumont Farm beginning in 2015, along with trial geophysical surveys (FDEM). The rich archaeological record encountered prompted an expansion of work to other areas of the battlefield and an increase in the scope of geophysical work (in the framework of this thesis).

Given the low magnetic background of the loess soil environment and the expected magnetic properties of many features of interest, magnetometry was identified as a key method. It was decided that FDEM would also be used in all survey areas, to provide a complementary magnetic susceptibility dataset, as well as the simultaneous collection of electrical data to assess contrasts in multiple properties. The multi-receiver configuration of the deployed FDEM sensor also allowed for the measurement of multiple depth volumes. Over 75 hectares were surveyed with both magnetometry and FDEM in mobile configurations. Given the relatively high conductivity of the fine silty soils, it was determined that GPR would be less useful due to signal attenuation. Furthermore, the uneven surfaces of more roughly ploughed fields presented potential challenges to ground coupling. Nevertheless, a trial application of GPR showed that it can successfully used if features are relatively shallow and present an appropriate contrast.

Magnetometry, with its greater sensitivity and sampling resolution, proved to be of particular use for the identification of small dipolar anomalies, the majority of which relate to ferrous metal objects (a subset of which are directly related to the battle). Comparison with systematically metal-detected assemblages of battlefield debris from the same areas (using conventional VLF detectors) showed high correspondence between the two datasets at the field scale. Additionally, the magnetometry data showed that ferrous metal objects were 'replenished' after certain intervals (several years) between detection and, further, that modern landuse was responsible for significant differences in distribution.

A variety of anthropogenic features were apparent in both magnetic and electrical datasets, including structures, brick kilns, property boundaries (ditches/walls), a quarry pit, and firepits from modern reenactments. Some of these features are shown on maps contemporary to the battle and indicate that: a) aspects of the maps are very accurate (thematically and spatially); and b) that some of the detected features may have played a role in the battle. Other expected features are conspicuously absent, notably graves and encampment-related features. This could relate to: a) a lack of contrast in their geophysical properties; b) post-depositional processes responsible for their erasure; or c) a true absence in the sample.

A programme of invasive sampling was undertaken simultaneous to the geophysical survey that allowed for more robust interpretation of the sensor data. This consisted primarily of boreholes in representative areas, as well as the measurement of geophysical properties *in situ*. Archaeological excavations were also undertaken in certain areas of particular archaeological potential. This exercise also revealed that many discrete magnetic features, morphologically indistinguishable from pit or ditch features, derived from concentrations of natural iron oxides associated with Tertiary marine deposits.

In all, the datasets clearly demonstrated the high potential of using large-area geophysical survey in battlefield archaeology to detect a wide range of features of interest. The multi-method approach was very useful in expanding the range of observable features and allowing a more thorough evaluation of the subsurface. Specific choice of instrumentation will depend on site characteristics, desired targets, and project scope such that it may be necessary to prioritize a particular method(s) over others. Here, the combination of FM and FDEM proved highly effective because of their differing (but complementary) characteristics in terms of sensitivity, sampling density, and operating principles. The data from Waterloo also illustrate the need for a targeted invasive sampling programme for a more complete understanding of sensor data. The lack of certain key features of interest is notable and underscores the need for further research into the geophysical properties of these targets to fully explain their absence. The influence of natural/geological features and their similarity to anthropogenic features also illustrates the perils of relying solely on sensor data in archaeological interpretations. It is thus clear that geophysical survey of battlefields must be part of larger integrated workflow, which fits well within the existing highly multidisciplinary traditions of conflict archaeology.

3. **What is the influence of soil erosion and deposition of colluvium on the archaeological record at Waterloo and how can we better understand its spatial extent?**

This question addressed what is likely the most immediate threat to the archaeological record at Waterloo (alongside illicit metal detection). While it has benefited from long-term protection (since 1914) against various forms of development, intensive agricultural landuse has resulted in accelerated soil erosion. This occurs primarily in the form of water erosion, which is prevalent throughout the Belgian loess belt, though tillage erosion and crop harvesting erosion also play an important role.

Soil erosion and accumulation of colluvium have several important impacts on the archaeological record of the battlefield. Erosion is likely to have resulted in the destruction of some ephemeral archaeological features and the movement of artefacts from their original depositional contexts. On the other hand, the deposition of colluvium in certain areas will have sealed other archaeological deposits of interest, potentially preserving them from post-depositional damage. The greater depth of burial in these areas, however, could complicate the use of certain methods of investigation. These issues were recognized at an early point in the archaeological project at Waterloo but knowledge of the extent and depth of colluvial deposits was limited to legacy soil mapping and coarse terrain analysis.

To obtain a higher-resolution mapping of colluvial deposits that could be applied to archaeological research questions, a variety of different (largely non-invasive) data sources were consulted. Borrowing from modelling work in broader soil science, important factors influencing water erosion were defined and isolated. Then, using recent high-resolution LiDAR data and landform extraction methods (Jasiewicz and Stepinski 2013), a more robust model of soil erosion and deposition risk was built; however, this still did not permit the direct (empirical) identification of colluvial deposits. For this, optical remote sensing and near-surface geophysical methods were used to identify proxies that were linked to colluvial deposits. Vegetation health indices (from Sentinel-2 multispectral data) and soil texture variability (from FDEM electrical conductivity data) provided particular insight. Combining these two data sources, which are influenced by similar physical properties but have different sampling resolution, sample support, and coverage, allowed for overcoming some of the limitations inherent to each. Targeted invasive sampling and laboratory measurements of key properties allowed for validation of the non-invasive data by linking measured variability to presence and depth of colluvial deposits. This framework will permit the refinement of archaeological sampling strategies and a more comprehensive understanding of the archaeological record of the battle in relation to the sedimentary environment.

Critical Perspectives and Future Work

This work demonstrates that geophysical survey can provide valuable insight into the archaeological record of early modern battlefield sites. This is particularly the case at the prospection scale (Gaffney and Gater 2003), where large-area surveys can be efficiently performed at relatively high resolution. This fills a much-needed gap between small-scale archaeological excavations and traditional prospection methods (e.g., test pitting) which have shown to be inefficient for battlefield sites. It is also highly complementary to the existing widespread methodology of metal detection survey that is central to the study of nearly any early modern battlefield. This reliance on metal detection methods makes the extension to other geophysical methods logical and consistent with existing workflows. This allows for insight into other forms of evidence, in addition to providing complementary information on metal scatters. Even features which at first glance do not appear to be directly related to the specific moment of a battle may provide important insights in terms of understanding landscape development over time. This is most obvious in the form of anthropogenic impacts, including earlier landuse and features which may have still been very prominent at the time of conflict as well as those post-dating it which may have impacted the archaeological record or indeed have some direct link to events of the past. Perhaps less evident are insights into environmental processes, demonstrated here in the examination of the sedimentary record of erosion and colluvial buildup. In both cases, this provided new perspectives and avenues of research into the archaeology of the Battle of Waterloo.

Nevertheless, geophysical survey is clearly not infallible when it comes to battlefield sites (or, for that matter, any type of archaeological site). This should not be taken strictly as an argument against the approach but rather underlines the necessity for recognizing certain shortcomings and integrating non-invasive methods within a larger archaeological workflow. In particular, a more thorough understanding of the expression of certain battlefield features of interest is still required. For the Waterloo dataset, it was demonstrated that burial and encampment-related features were not detected with the deployed methods (FM and FDEM). Given the sample size and results at similar sites, however, it is expected that such features should be present. In certain cases, then, geophysical survey is perhaps not (yet) capable of matching the results obtained from other methods such as systematic test trenching (Bosquet et al. 2015; Danese 2020; Moulaert, Sosnowska, et al. 2020).

Given the variety of ongoing threats to archaeological sites (most obviously in the form of anthropogenic disturbances but also less obvious threats such as soil erosion), the development of efficient methods of investigation is crucial. Battlefield sites are particularly threatened, as the archaeological resources they hold are often not readily visible nor their value particularly obvious to the broader public and, perhaps more crucially from a preservation standpoint, to stakeholders such as approval authorities, developers, and landowners. Here, geophysical survey has an important role to play as an efficient large-scale prospection method for initial characterization of potential features of interest and prioritization of research goals. This could potentially be extremely useful from the standpoint of site management and for supporting protection of threatened archaeological landscapes, which has been a recurring difficulty for battlefield heritage around the world (Civil War Sites Advisory Commission 1993; Banks and Pollard 2011; Foard and Morris 2012; Crowder 2021).

As has been frequently noted throughout this thesis, it is imperative that geophysical survey be combined with other methods. As suggested in Chapter 2 and demonstrated in Chapter 4, this includes a sampling strategy involving targeted minimally-invasive investigation, as well as more traditional forms of archaeological investigation. There is also the need for incorporating other forms of ancillary data (e.g., data from soil surveys, historical documentation, and remote sensing products including air photos and LiDAR). In this regard, battlefield archaeology is very well-positioned, given the existing multi-disciplinary emphasis of the discipline. This larger integrated workflow allows for a more robust understanding and contextualization of non-invasive datasets.

A more complete integration of geophysical survey into battlefield archaeology will rely on the continued development of our understanding of the geophysical expression of features of interest. This is still an area of limited understanding, as a robust definition of the archaeological signature of some elements of battlefield landscapes is still being developed (e.g., see Poulain et al. 2022 on encampments). Thus, there is still a high degree of ambiguity in the interpretation of geophysical datasets from battlefields, particularly when dealing with palimpsest/multi-occupation sites and where only limited validation data obtained through sampling is available (e.g., Trinks et al. 2022). Sampling of features encountered during archaeological excavation to characterize their geophysical properties relative to the background (e.g., Verhegge et al. 2023) is thus of paramount importance for determining which (if any) approach and instrument type will be most suitable. The creation of large databases of geophysical datasets from battlefield sites using different methods will also be useful for comparative analyses. While the background characteristics and specific burial environment (preservation and post-depositional processes) will have a large impact when comparing different sites, this can be accounted for in forward modelling.

A point worth reiterating again concerns the practical challenges posed by the terrestrial deployment of geophysical methods as presented here. In the parcelled and cultivated landscape of Waterloo, this required considerable logistical work to organize permission of access from landowners and time surveys according to short and often unpredictable windows offered by the agricultural cycle. The result is that, even in these mostly ideal conditions for geophysical survey (unobstructed and generally level terrain), complete survey coverage requires a long-term and highly flexible approach. Evidently, however, other methods of investigation will face similar challenges, perhaps even more so when more invasive work is planned.

In more challenging landscapes with obstructions to motorized survey as used here (such as forested areas), different and often less-efficient survey configurations will be required. In this regard, however, significant advancements are also being made in the use of UAV-deployed geophysical sensors (Schmidt, Becken, et al. 2020; Stele et al. 2022), though important challenges still remain with regards to upscaling and data quality (Trinks et al. 2023, p. 396). Notably, there will necessarily be a reduction of sensitivity compared to ground-based survey, though results are increasingly promising (Stele, Kaub, et al. 2023). In addition to potentially allowing for survey in difficult terrain, low-altitude UAV survey could be a way for mitigating logistical challenges associated with survey in areas where access via more invasive survey configurations can be severely limited (i.e., in the case of motorized survey in arable land considered here).

Other promising developments, though still not in widespread use, include multi-sensor platforms incorporating several different geophysical techniques and allowing for the collection of larger datasets simultaneously. This not only increases the survey efficiency (i.e., compared to the need for repeat surveys with different instruments) but also presents additional opportunities for data fusion and joint inversions which may allow for more robust archaeological interpretations and wider applications. If battlefield archaeology can continue to take advantage of advancements in the broader field of archaeological prospection (Trinks et al. 2023), it may be possible to unlock further potential, thus increasing survey efficiency and efficacy for these complex landscapes. Such methodological breakthroughs have been paramount to the development of battlefield archaeology and are likely to continue to influence the direction of the discipline.

In closing, it is important to emphasize how the research described herein, which is focused on a relatively narrow set of methodological approaches, connects with the broader enterprise of battlefield/conflict archaeology. At its core, the discipline seeks to explore the human experience of conflict through its material remains, thereby enhancing existing narratives mostly centred around historical accounts (whether documentary or oral). A fundamental objective is, therefore, the efficient identification of these remains (i.e., prospection). This work addresses this challenge with a particular focus on the landscape scale that characterizes the majority of conflict sites. The next step involves an archaeological/anthropological lens which relates material remains to physical landscapes and human experience, lending additional context that is often absent from historical accounts (Stele et al. 2021, pp. 180–181). This emphasis on physicality underlies the notion of conflict landscapes, which examines how landscapes have been created and transformed through war. This has been a particularly important theoretical perspective in the study of 20th-century conflict (Carman and Carman 2006; Saunders 2012; Saunders and Cornish 2021) but is equally relevant for earlier landscapes of conflict. If the goal of conflict archaeology is to shed light on these landscapes (largely through their materiality) from genesis to various stages of transformation, then an efficient approach to their prospection is a fundamental starting point.

As has been recently pointed out (Banks 2024), the perspectives provided by conflict archaeology remain enormously relevant in the context of continuous conflict around the world. Studying conflicts of the past, particularly through an archaeological lens, allows for nuanced understanding of the impact of war on individuals, landscapes, and broader society (both military and civilian). Historical battles and conflict sites of note continue to capture considerable public interest. These events, though sometimes romanticized in various forms of media, represent terrible but persistent and universal expressions of human behaviour through time. Many battlefields around the world have been preserved and presented as heritage sites attracting considerable numbers of visitors. These often-idyllic landscapes of the present can seem far removed from the brutal episodes for which they are famous.

There has long been concerted historical interest in the study of battlefields, though professional historians have also decried the lack of serious academic interest in military history compared to works aimed at popular audiences or those produced within and for the military establishment (McNeill 1980c, pp. 99–100). For better or for worse, the enormous popular interest in historical battles has ensured that a plethora of information and media is produced on the subject. While a more recent trend in military history has been a shift towards 'war and society' (a nuanced approach that examines conflict in the broader context of social history (Beckett 2016)), there remains a specific interest in particular events surrounding battles themselves.

Older (pre-20th century) conflict landscapes may be particularly susceptible to romanticization, especially where they do not hold readily evident reminders of the brutality of their past. Waterloo is such an example and archaeological research, supported by geophysical prospection, is shedding light on the horrific events that took place by bringing us face-to-face with their material remains (Pollard

2020; Wilkin et al. 2023). This necessitates a reframing of our understanding of the battle and is quite separate from the politically-influenced narratives that have characterized discourse of the battle over time (Heinzen 2014), which are somewhat divorced from the material and physical dimension. While hinted at in historical narratives, this visceral nature becomes especially apparent in the present when dealing with archaeological (and human) remains. This connection is especially tangible when it relates to a shared experience, and this has been a profoundly important component of the Waterloo Uncovered project, which actively involves military veterans and serving personnel, some of whom are members of units that served at the Battle of Waterloo (Evans et al. 2019). Beyond the obvious impact on those who were direct participants in the battle, archaeological research is also providing insights into enduring landscape transformation and non-combatant experiences by documenting impacts on existing (civilian) infrastructure (e.g., structures and quarry pit at Hougoumont) and evolving components of the landscape (e.g., mobile forge near the Lion Mound, likely related to post-battle cleanup or memorialization). Geophysical prospection has been a key component of the larger archaeological project at Waterloo from the beginning (De Smedt 2017). The geophysical surveys described herein have continued to influence the direction of the archaeological research (Bosquet et al. 2023, 2024), while results of excavations have informed the interpretation of the geophysical datasets. This feedback loop is a crucial framework for the integration of non-invasive datasets into broader archaeological research, as detailed above.

Armed with a robust prospection dataset gained via the critical application of a range of methods, archaeologists can begin to investigate the materiality of landscapes, thereby gaining an enhanced understanding of the creation and transformation of conflict landscapes over time (a longitudinal perspective that is an inherent strength of the archaeological approach). At the smallest scale, this can even yield insights into the impact of conflict upon individuals. To date, only a small part of the large non-invasive dataset gathered at Waterloo has been investigated archaeologically, but it forms a critical starting point for investigating the conflict landscape.

Ultimately, the study of conflict must be a multidisciplinary endeavour, combining a range of archaeological methods and theoretical frameworks, as well as those from other disciplines (Stele et al. 2021). Archaeological perspectives offer certain unparalleled insights, but these must also be contextualized using information from other research avenues. The material insights offered by archaeological research must foremost be grounded in a solid framework of archaeological prospection. While this is a crucial first step to a robust research process centred around materiality, it is indeed only the beginning. The following necessary challenge then lies in linking physical contrasts and material evidence (using a kind of middle-range abstraction (Raab and Goodyear 1984)) to the more nuanced human experience of war that is the end goal of conflict archaeology.

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