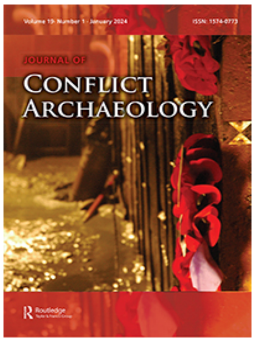

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# Geophysical approaches to the archaeological prospection of early modern battlefield landscapes: a review of methods and objectives

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**ABSTRACT**

This paper reviews methodological approaches in battlefield archaeology with a focus on sites of the early modern period, ca. 17th-19th century. The challenges associated with the prospection of these sites partially explains the relative lack of serious research in this area until the late 20th century. While acknowledging the foundational role of conventional metal detection in overcoming these difficulties, it is argued that other less widely deployed geophysical methods should be increasingly used as part of an integrated approach to studying battlefield landscapes. Targets of interest are reviewed alongside the geophysical properties that might enable their detection and a selection of case studies successfully deploying these approaches within battlefield archaeology and adjacent disciplines are considered.

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Battlefield archaeology; methodology; non-invasive prospection; near-surface geophysics; remote sensing

## 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 (Banks 2020; Foard et al. 2003; Freeman 2001; Homann 2013; Pollard and Banks 2005; Scott and McFeaters 2011). This paper 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 the collection and analysis of increasingly large, high-resolution datasets.

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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, 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, 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, 729). In essence, battlefields pose a methodological challenge and have perhaps suffered in the past from a scepticism 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 (Balicki 2011; Corle and Balicki 2006; Smith 1994). 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. Corradini et al. 2022; Fitton et al. 2022; Verhegge et al. 2021). 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, 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; Stele, Schwickert, and Rass 2021; van der Schriek 2020).

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 paper, 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 engagement of massed infantry armed with muzzle-loaded weaponry, supported 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 paper 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. 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 (Pollard 2009b; Scott et al. 1989). 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 characterization of electromagnetic properties in the near-surface environment: namely electrical conductivity, dielectric permittivity, and magnetic susceptibility/permeability. Instruments include magnetometry (Aspinall, Gaffney, and Schmidt 2008), ground-penetrating radar (GPR) (Conyers 2013), electromagnetic induction (EMI) (De Smedt 2013), and electrical resistivity (or resistance) (Schmidt 2013) survey. Metal detectors (Overton and Moreland 2015) form a specific sub-section 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.

Magnetometry is the most widely employed method in archaeological geophysics (Aspinall, Gaffney, and Schmidt 2008). 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

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 | **** | * | * | * | * | * |

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 deep 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. Li 2003; Murdie et al. 1999), this is complicated by the use of potential fields in these methods versus waves in GPR. In practice, this 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 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 1980; Tabbagh 1986) 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 vs. 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 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 (Dabas 2009; Loke et al. 2013; Panissod et al. 1998). 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. Here, we outline 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, McBride, and Willison 2021, 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. Farley, McBride, and Willison 2021; Harrington 2005; Homann 2013; Sutherland 2005), 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, and Sarris 2020). A particular response can be conceptualized as either signal or noise, depending on the aims of a geophysical investigation. 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, 90) but continuing as well into the mid-18$^{th}$ 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 lead 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 19$^{th}$ 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. Eve and Pollard 2020; Pollard 2009a). 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 of course more rarely recovered from battlefield sites as they were frequently scavenged shortly after (Pollard 2021, 79; Sutherland and Schmidt 2003, 22). 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, Gaffney, and Schmidt 2008; Haxell and Triggs 2012; Wiewel and De Vore 2018) or other EMI instruments (e.g. de Smet et al. 2012; Pertermann and Everett 2015; Saey et al. 2011, 2016) (Figure 1). 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

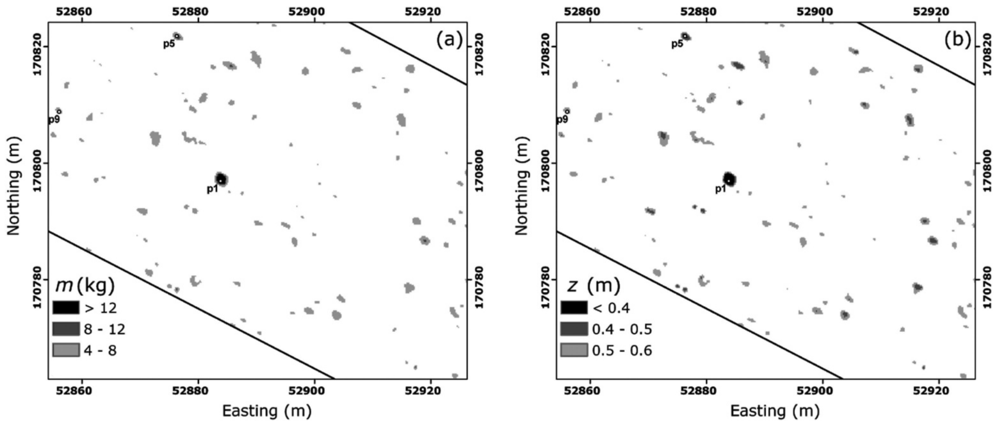


Figure 1. An example of modelled mass (left) and depth (right) of metal anomalies at a WW1 battlefield based on electrical conductivity of multiple coil pairs from an FDEM dataset. Validation of the dataset yielded ordnance or shrapnel at all (20) sampled locations where metal was predicted. Reproduced with permission (Saey et al. 2011Figure 10).

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.

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-decimetre 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; 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, Doro, and Bank 2020)) in battlefield archaeological frameworks. Applications of forensic geophysics have used similar methods to detect buried objects of forensic interest such as weapons (Dionne et al. 2011; Hansen and Pringle 2013; Rezos et al. 2010, 2011; 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 (de Smet et al. 2012; Heckman 2005), 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 electric (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; Note, Gheyle, et al. 2018; Note, Saey, et al. 2018; Saey et al. 2016). 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 20$^{th}$-century conflict sites, but these examples show the potential of these methods. Similar approaches have been suggested at earlier conflict sites (Bevan 2004, 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, 24). Despite this, relatively few mass graves from battlefields have been conclusively identified (A. A. Curry and Foard 2016). A considerable amount of literature (Berezowski et al. 2021; Bevan 1991; Cheetham 2005; Gaffney et al. 2015; Pringle et al. 2020) 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, 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. Bonsall and Cian 2021; Masters and Enright 2011; Patch et al. 2015; Pollard 2011; Schürger 2015; Sherrod et al. 2020; Sutherland and Schmidt 2003), 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, Andreas, and Daniela 2022), or the presence of associated (metal) items or other grave furniture (Půlpánová-Reszczyńska, Půlpán, and Křivánek 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, 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 negative 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, 77–79). There are, however, some notable archaeological examples where the phenomenon of immediate backfilling of graves resulted in lasting anomalies (Fassbinder 2015) (Figure 2). Magnetic enhancement of a grave fill in the presence of microbial activity enabled by the decaying remains has also been theorized (Cheetham 2005, 78), though few examples have been reported and it can be difficult to distinguish this enhancement from other magnetic forms (Juerges et al. 2010; Linford 2004). 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 re-oxidation can readily occur (Dent 2004). 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, Andreas, and Daniela 2022), either from thermoremanent magnetism if the Curie temperature is surpassed or through ferrimagnetic enrichment of iron oxides.

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

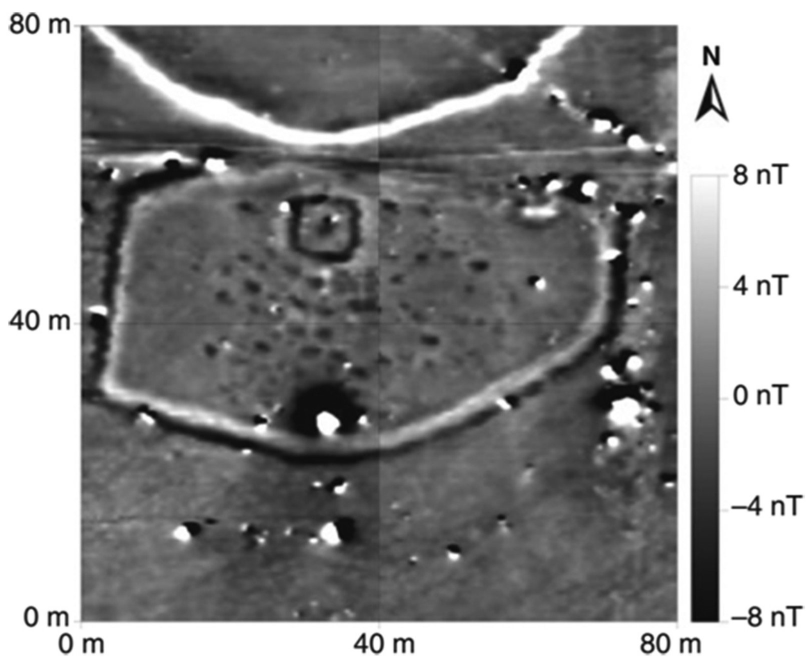


Figure 2. Example of magnetometry dataset with single grave features appearing as negative (dark) anomalies at a 17th-century cemetery in Kazakhstan. Reproduced with permission (Fassbinder 2016). Figure 6

consistently in archaeological settings. There are reported examples of graves appearing as either conductive (e.g. Bevan 1991) and 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, Metje, and Chapman 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 archaeological and forensic literature (Berezowski et al. 2021; Bevan 1991; Cheetham 2005) 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.) (Figures 3 and 4). 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).

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, 370) 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). Finally, 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 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 19$^{th}$-century conflicts and typified the global conflicts of the early 20$^{th}$ 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.

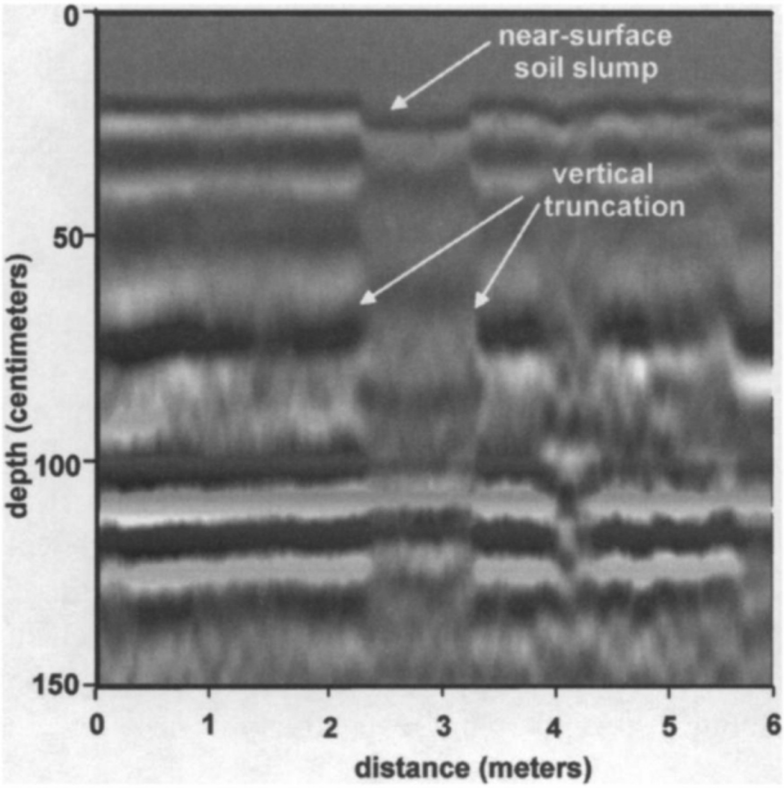


Figure 3. A likely grave shaft (without casket) seen in a GPR profile, identified by the interruption of the natural stratigraphy and low-amplitude reflections within the fill. Reproduced with permission (Conyers 2006) Figure 4 Figure 4.


Figure 4. 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).Figure 2

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 (Drass, Vehik, and Perkins 2019; Kvamme and Wiewel 2013) that were particularly common in various parts of the United States. More permanent fortifications are particularly suitable to geophysical survey (Figure 5), 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, Mink, and Stephen McBride 2017; Holas 2022) to more substantial offensive or defensive elements of prolonged sieges (Dacko et al. 2021; Haxell and Triggs 2012; Orr and Steele 2011) to quasi-permanent fortifications (Verschoof 2014), all of which have been successfully investigated using geophysics (Figure 5, Figure 6, Figure 7). In some cases, features of varying physical and time 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

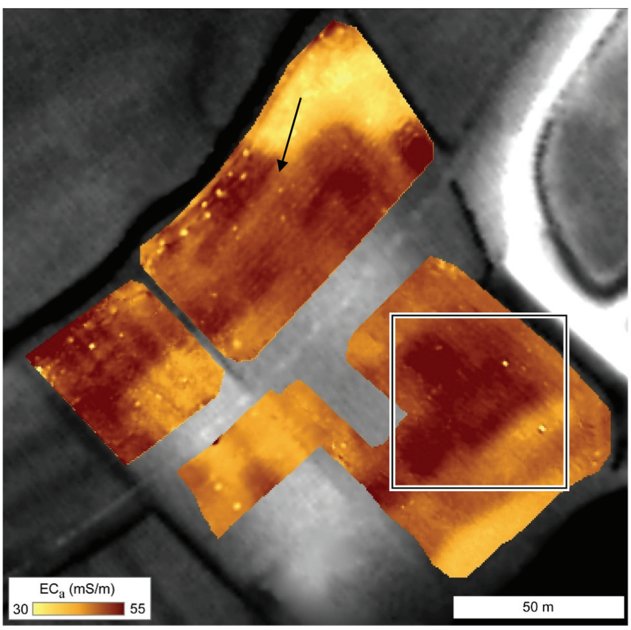


Figure 5. An apparent conductivity dataset from an EMI survey, showing bastions/ramparts (high conductivity, example indicated by the bounding box) and ditches (lower conductivity, example indicated by the black arrow) associated with a 17th-century Spanish fortification in Belgium (Poulain and De Clercq 2015, 634).

of the use of seismic survey for the characterization of earthwork features associated with Hadrian's Wall (Goulty et al. 1990).

Tunnels are another target for which seismic methods have been successful (Sloan, Miller, and Steeples 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-20$^{th}$ sites but have long played a role in warfare, particularly in siege operations (Olson and Speidel 2020; Springer 2015). 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).

### *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, 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 (Balicki 2011; Whitehorne 2006), 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, Brion, and Verbrugge 2022) to study the archaeological remains of the entire range of these sites from various periods with the longer-term encampments best represented in the archaeological record (Geier, Orr, and Reeves 2006; Lemaire 2020), although short-term occupations associated with more mobile armies have also been identified (Danese 2020; Drnovský, Hejhal, and Průchová 2021; Kalos 2015). 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 at these sites, often in combination with metal detection and/or excavation (Balicki 2016; Barker 2015; Hadley and Richards 2016; Parrington 1979; Patch et al. 2015; Simon et al. 2019; Trinks et al. 2022; van der Schriek 2020). 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, Brion, and Verbrugge 2022, 2) and here again we suggest that geophysical prospection has an important role to play.

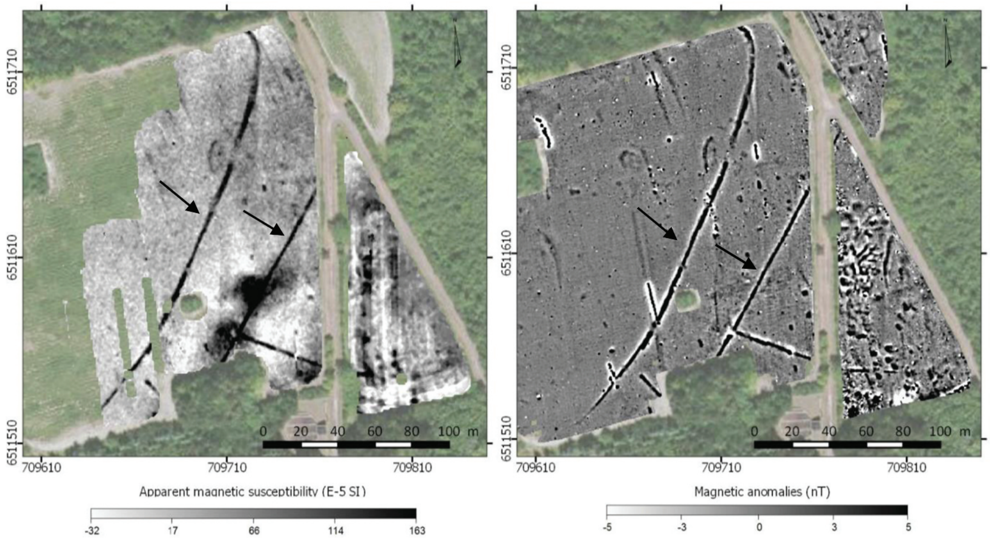


Figure 6. Magnetic susceptibility (EMI – left) and flux density (magnetometry – right) data showing ditch features (linear strongly magnetic anomalies indicated by arrows) associated with the Roman siege of Gergovia, France. Reproduced with permission (Simon et al. 2019Figure 2).

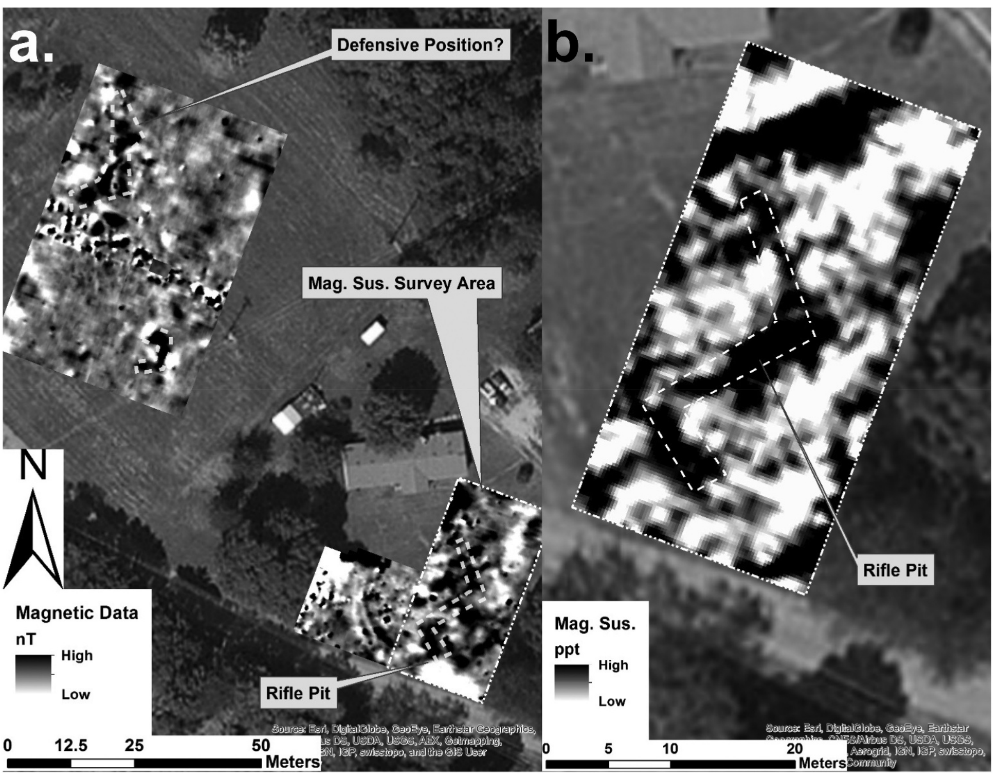


Figure 7. Magnetic anomaly in magnetometry and EMI data associated with a Civil War rifle pit at Tebbs Bend, Kentucky, USA. Reproduced with permission (Henry, Mink, and Stephen McBride 2017).

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, 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, 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 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, 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 (Drnovský, Hejhal, and Průchová 2021; van der Schriek and Beex 2017, Figure 4) and have been identified with magnetic surveys (Barker 2015) (Figure 8). Whitehorne (2006, 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, 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.

### *Key terrain – anthropogenic landscape*

Another broad category of evidence to be considered are 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 networks 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 2015b, 33–34). This track, along with the wood through which it passed, is no longer present in the modern landscape.

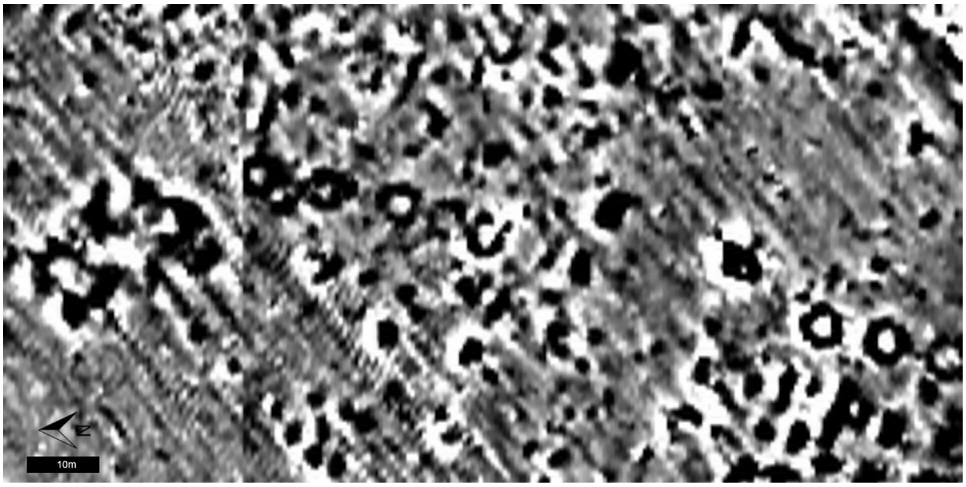


Figure 8. Magnetometry dataset from an 18th-century military encampment in Dorset. The annular features in the centre of the image are interpreted as remains of cookpits/field kitchens. Reproduced with permission (Barker 2015 Figure 9).

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 (S. S. 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, 142–143).

Field boundaries 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, 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 9).

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, 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) (Figures 9 and 10), which could assist in targeting excavations (Broadbent and Ervin 2014; Doolittle 2009; Pollard 2011, 108).

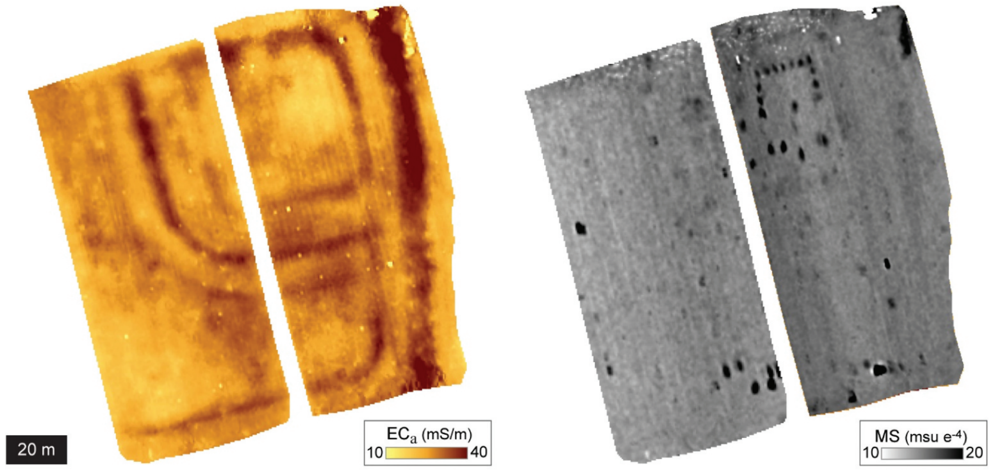


**Figure 9.** EMI dataset showing clear electrical contrasts (left) indicating enclosure ditch features at a medieval abbey in Belgium. Note also the rectilinear feature visible at top right in the magnetic susceptibility data (right), the individual anomalies of which represent brick structural foundations (De Smedt, Van Meirvenne, et al. 2013).

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 (Brown 2021). In brief, KOCOA is essentially a form of viewshed and cost surface analysis that analyses physical features in the landscape in terms of their ability to restrict visibly and movement,

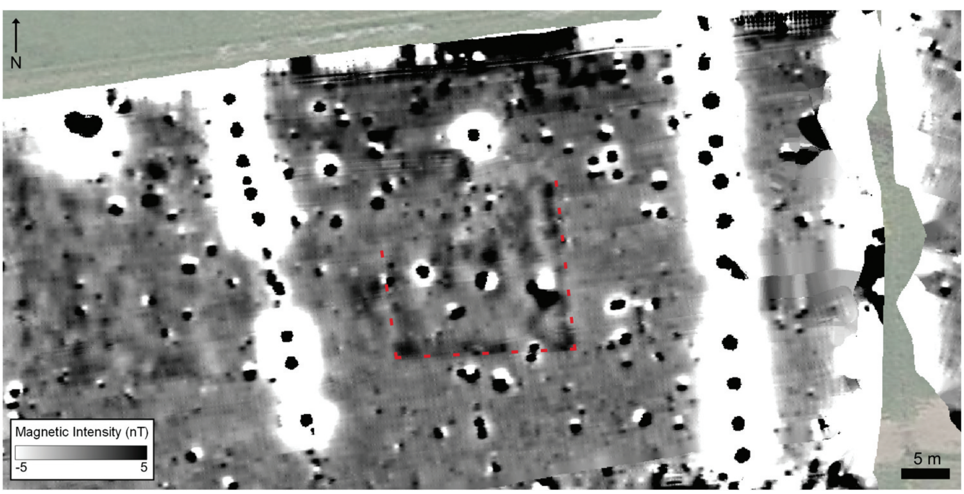


**Figure 10.** Magnetometry dataset from the battlefield of Waterloo showing rectilinear anomaly outlined in red, which was revealed to be the remains of a 19th-century brick structure upon excavation (Bosquet et al. forthcoming 2023).

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 (E. D. 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 20$^{th}$ century (e.g. Juhász and Neuberger 2015; Storch et al. 2021; van der Schriek and Beex 2017) 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, 12). Geophysics represents a possible avenue for delineating these different phases of land use when informed and validated by targeted excavations.

### 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 (Corradini et al. 2022; De Smedt, Saey, et al. 2013; De Smedt, Van Meirvenne, et al. 2013; Schneidhofer et al. 2017). These techniques rely primarily on electrical contrasts which can be related to pedological variations and specific buried deposits and have been undertaken using large-scale electromagnetic methods (FDEM and GPR) (Figure 11).

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

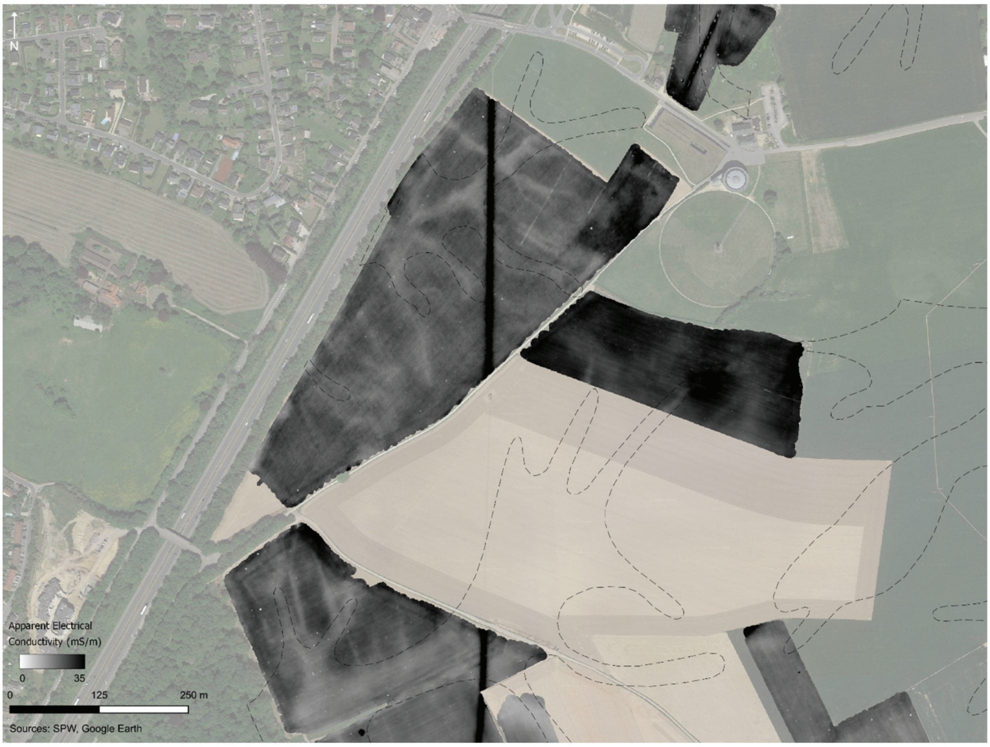


**Figure 11.** Apparent conductivity data from FDEM survey at the battlefield of Waterloo. Dashed lines indicate colluvial deposits (eroded soils) mapped in the mid-20th century (Louis 1958). These correlate with low-conductivity (lighter-toned) features in the FDEM dataset, providing more detail on the distribution of these deposits.

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 is particularly relevant in battlefield archaeology, however, given the reliance on the conventional metal detector, which has limitations in its depth of exploration. While artefacts are shallowly buried at most battlefield sites, there are also many cases of deeply buried horizons (such as colluvial or alluvial deposits) (Ball 2016, 273; Bradley 2022; Foard, Janaway, and Wilson 2010; Sutherland 2016) 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 (Bradley and Arnold 2017; Schürger 2015, 121; Waterloo Uncovered 2015a) 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,[5] particularly those with high magnetic susceptibility (Farley, McBride, and Willison 2021; Igel, Preetz, and Altfelder 2009). 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 perhaps better defined as noise (Schmidt, Dabas, and Sarris 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. We argue 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' (Noël Hume 1969, 188). Some researchers have emphasized the importance of situating battlefields in their landscape context (Foard and Partida 2018, 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 (Ball 2016, 277). 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 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; 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, De Smedt, and Verhegge 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 (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 can be developed which is particularly important for the increasingly large geophysical data sets being produced (Hinterleiner 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, 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; Gustavsen et al. 2020; Trinks et al. 2018). This has also been recognized in battlefield archaeology with Curry and Foard (2016, 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 article 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 characterization 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 fields.

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 (Cheetham 2008; Kvamme 2003). 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 contextualizing 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.

## Notes

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 prescribed manner (Corle and Balicki 2006, 56).
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.
3. An associated geochemical enrichment may still be present (Oonk, Slomp, and Huisman 2009) but this is not yet a widely used method for the detection of archaeological burials.
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, 20). Flanking entrenchments were also planned at the nearby village of Braine l'Alleud but ultimately not completed (Glover 2014, 106).
5. 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, 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 (Kibblewhite, Tóth, and Hermann 2015; Linford 2004; South 2002, 159).

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## Disclosure statement

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## Notes on contributor

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