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

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ABSTRACT

Archaeological prospection is continually expanding into new frontiers, examining increasingly large areas, diverse environmental contexts and varying site types. One area that has received only limited focus is historic battlefields. This paper presents results from large-scale geophysical surveys (> 100 ha) at the Napoleonic battlefield of Waterloo (1815) in Belgium, using fluxgate magnetometry and frequency-domain electromagnetic induction. Despite its international historical significance, professional archaeological research at the battlefield is still in its infancy. We demonstrate how important insights can be gained by using geophysical methods for identifying features and artefacts related to the battle and for developing an understanding of the various influences acting on the present landscape. The largest survey of its kind undertaken on a single battlefield site, this approach holds particular potential for battlefield archaeology, given the subtle and low-density nature of the sought-after targets and the extensive area of the site. Such an approach can mitigate (though not entirely resolve) challenges of resolution and scale associated with other methods of investigation. Using a representative range of examples from Waterloo, we consider successes and challenges in undertaking geophysical surveys on battlefield sites. An integrated approach that incorporates targeted sampling and other forms of ancillary data is emphasized for a more robust interpretation of noninvasive sensor data.

1 | Introduction

Advances in geophysical instrumentation and processing in recent decades have enabled the prospection of increasingly large areas, such that the high-resolution mapping of landscapes spanning hundreds of hectares is now possible (Trinks 2015). This has been a particularly important development for the investigation of large archaeological landscapes (Darvill et al. 2013; De Smedt et al. 2022). Battlefields are an example of such a site, typically characterized by unstratified scatters of artefacts and ephemeral features related to fleeting moments of activity spread across very extensive areas. Nevertheless, large-scale geophysical surveys of battlefields have remained relatively rare, with limited exceptions (e.g., Note, Saey, et al. 2018; Simon et al. 2019). We present data from large-scale multimethod surveys at the battlefield of Waterloo, Belgium, representing, to our knowledge, the largest dedicated geophysical survey undertaken at a single battlefield site (> 100 ha). We consider the outcomes of the survey, with respect to a set of defined targets, and address some of the challenges associated with the collection and interpretation of data from (early modern) battlefield sites.

2 | Research Context

The Battle of Waterloo, fought on the 18th of June 1815, famously saw the defeat of Napoleon Bonaparte's French army by a pan-European coalition led by the British Duke of Wellington and Prussian Marshal von Blücher. This marked the end of an offensive campaign launched by Napoleon across the French border into Belgium and brought a decisive end to the Napoleonic wars in Europe. Separate battles were fought in the days leading up to June 18th with the armies regrouping at Waterloo for the decisive engagement. Wellington's Anglo-Allied army (composed of British, German and Dutch troops numbering approximately 70 000) was deployed along a ridge and reverse slope (a front of approximately 2 km) with Napoleon's army (approximately equal in size) positioned on an opposing ridge some 1500 m to the south (Adkin 2001). The battle began late in the morning and continued through to the late evening. Cavalry and infantry assaults supported by artillery were launched throughout the day by both sides with heavy casualties incurred (exact numbers unknown (Pollard 2021, n. 32) but certainly in the thousands). 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. For more detailed accounts of the battle, readers are referred to other plentifully available references (Adkin 2001; Chandler 1980; Glover 2014; Muir 2013).

The site is located in central Belgium, approximately 15 km south of Brussels in the country's French-speaking region of Wallonia (Figure 1). Despite its historical significance, professional archaeological research on the battlefield has been (paradoxically) quite limited until very recently. This is in part because the battlefield has been afforded legislative protection from large-scale disturbances since 1914 (the first site so designated in Belgium), thus not necessitating any preventive (development-led) archaeological intervention (the dominant form of archaeological fieldwork in Wallonia). Beginning in 2012, however, developments associated with the battle's bicentenary spurred limited archaeological work, the most significant discovery of which was the skeleton of a Hanoverian soldier (Bosquet et al. 2015). Thereafter, a major turning point occurred with the initiation of the Waterloo Uncovered project in 2015, which combines archaeological research with wellbeing and recovery programmes for military veterans and serving personnel (Evans et al. 2019). Several important areas across the battlefield have been investigated over a series of campaigns (Bosquet et al. 2016, 2017; Moulaert et al. 2019; Moulaert et al. 2020; Waterloo Uncovered 2015a).

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,

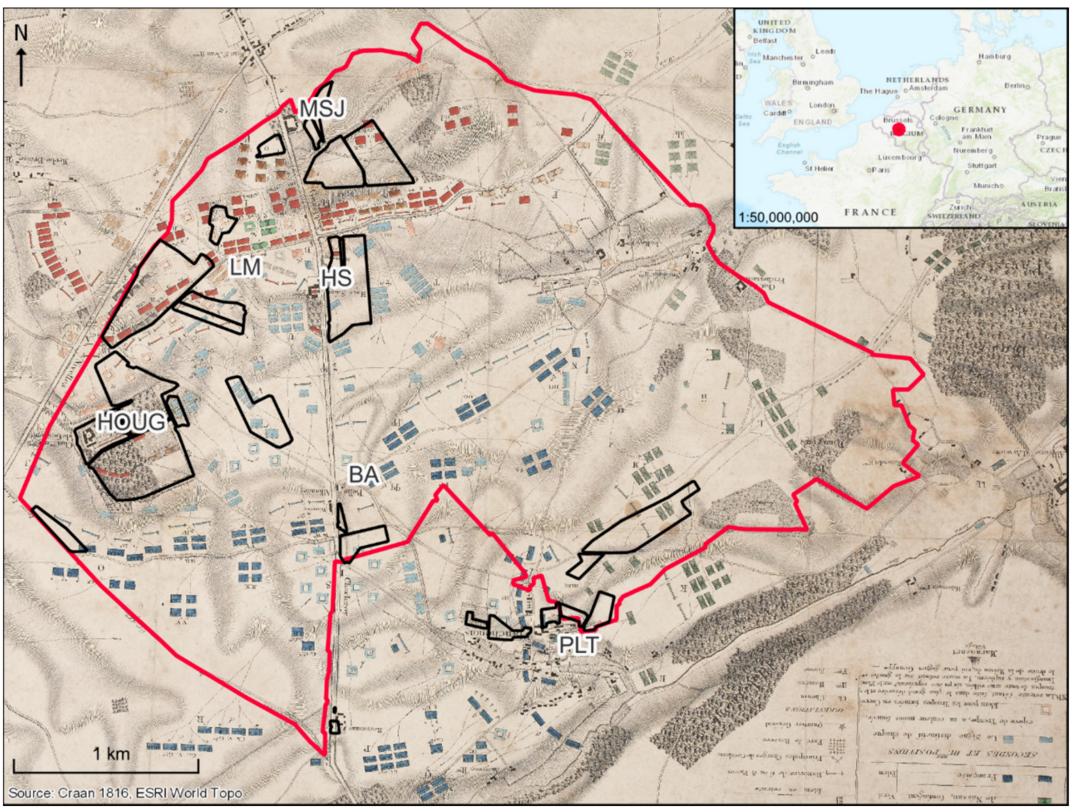

FIGURE 1 | Overview of battlefield on 1816 map, showing Anglo-Allied (in red at top), French (in blue at bottom) and Prussian (in green, lower right) deployments. The red boundary marks the zone under legislative protection. Survey areas outlined in black (totalling 105 ha). Basemap: Plan du Champ de Bataille de Waterloo, W.B. Craan, 1816 (British Library). Annotated locations mentioned in text: Hougoumont (HOUG) Farm, Lion Mound (LM), Haye Sainte (HS) Farm, Mont-Saint-Jean (MSJ) Farm, Belle Alliance (BA) and Plancenoit (PLT).

sec. 10). Archaeological research has the potential to shed light on some of these. 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 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 MSJ, 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 (Bosquet et al. 2023; Eve and Pollard 2020).

Geophysical surveys were undertaken at a very early stage of the Waterloo Uncovered project, focussing on the immediate area around Hougoumont (De Smedt 2017). These pilot efforts indicated that the site was well-suited to noninvasive prospection (given its relatively homogenous soil conditions with a stable low-noise background, accessibility for large-scale motorized survey and minimal anthropogenic disturbances) 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.

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 elsewhere (Pollard 2009; Scott and McFeaters 2011). Alongside this work, more traditional forms of archaeological excavation have explored other features. We believe that geophysical survey holds 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 sections, we consider this range of targets—metal artefacts, burials, field fortifications, encampments, other anthropogenic terrains and relevant environmental information—following the framework presented in Williams et al. (2024) 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).

3 | Methods

The two primary methods used were frequency-domain electromagnetic induction (FDEM) and fluxgate magnetometry. For the FDEM surveys, a DualEM-21H sensor (DualEM, Canada) was used in horizontal coplanar (HCP) mode. This configuration allows for deeper penetration compared to the vertical coplanar (VCP) mode (McNeill 1980), while also allowing for a qualitative determination of depth of certain magnetic anomalies based on the sign change that occurs in the cumulative in-phase response of this geometry (Tabbagh 1986a; De Smedt 2013, pp. 111–114). While this ambiguous response can complicate straightforward interpretation of a single coil pair, this is overcome by the simultaneous recording of a perpendicular (PRP) response that does not suffer from the same behaviour. The instrument has a transmitting coil operating at 9 kHz, three pairs of receiving coils (coplanar to the transmitter at 0.5, 1 and 2 m spacing and perpendicular at 0.6, 1.1 and 2.1 m) and a factory-set sampling rate of 8 Hz. For shorthand, the coil configurations will be referred to as HCPH/HCP1/HCP2 and PRPH/PRP1/PRP2 with the relevant signal component appended (IP for in-phase and QP for quadrature-phase). The QP component is linearly proportional to the apparent electrical conductivity (ECa) while the IP component is related to apparent magnetic susceptibility (MSa) in a low induction number setting, which assumes low operating frequency, small coil separation and relatively low conductivity (< 100 mS/m) (Callegary, Ferré, and Groom 2007; McNeill 1980; Tabbagh 1986b). Thus, crucially, it is the only geophysical method that allows for the simultaneous recording of electrical and magnetic variations. A transect interval of 2 m (with 0.25 m in-line spacing) was used to target large archaeological features and pedological variability. Drift corrections were applied using the tie-line method described by Delefortrie et al. (2014). For uniform visualization of the entire dataset, median levelling was applied to the MSa data and edge matching for the ECa. The FDEM dataset covers approximately 106 ha (Figure 2, Figures S1 and S2).

Magnetometry 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, each with a sampling rate of 100 Hz (down-sampled to 0.1 m in-line spacing), was used. The 0.5 m transect interval was chosen to provide a balance between resolution and survey speed, given the expected size of targeted features and following more generally accepted guidelines in archaeological prospection (Schmidt et al. 2015, p. 64). A zero-median traverse procedure was applied to each transect (unique sensor) to remove the influence of heading errors. The magnetometry dataset covers approximately 80 ha (Figure 2, Figure S3).

For both instruments, measurements were performed in mobile configurations with the instruments towed behind a utility quad bike. For the FDEM sensor, this was accomplished using a metal-free sled with the instrument 0.165 m above the ground surface and 3.45 m behind the towing vehicle. The magnetometer array was towed using a cart and towbar system composed of a variety of nonferrous materials (aluminium, brass and wood). 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 GNSS (either Leica Viva GS15 [Leica Geosystems, St. Gallen, Switzerland] or Trimble R10 [Trimble Inc., Westminster, USA]) with RTK corrections (typical accuracy < 10 cm) supplied via mobile network, synchronized to

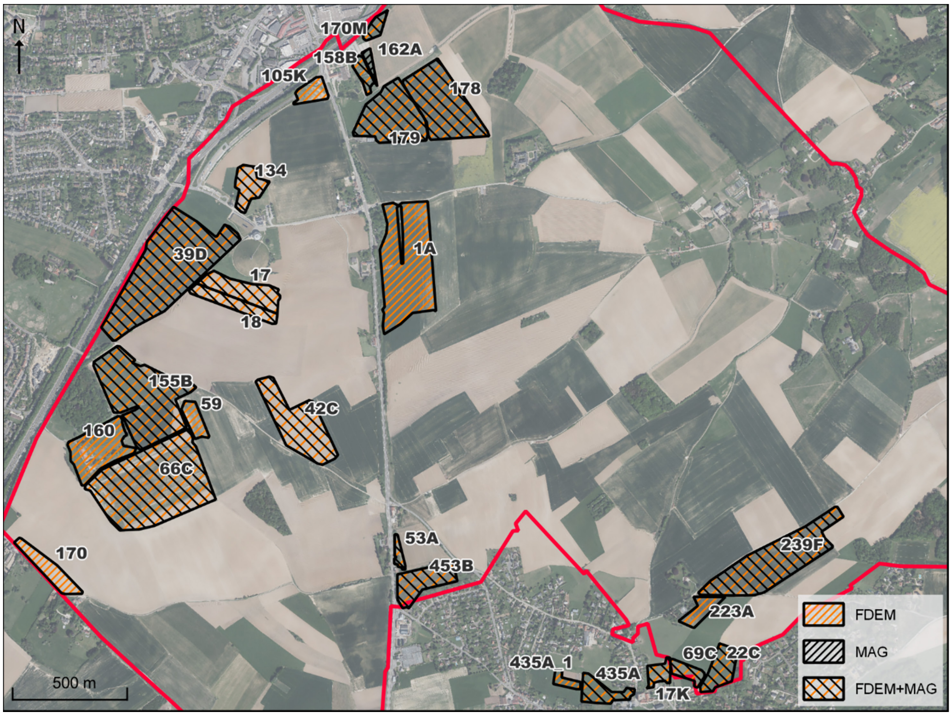

FIGURE 2 | Overview of survey areas showing different methods employed. Labels are derived from cadastral IDs and are unique parcel identifiers, mentioned below when discussing individual anomalies. Orthophoto basemap (2022) from Géoportail de la Wallonie.

instrument readings with timestamps. Surveys were predominantly undertaken between June and November 2022. Offsets relating to seasonal (moisture) differences impacting electrical data were corrected when necessary using edge matching but were generally minor. Field conditions were variable but mostly consisted of lightly tilled bare fields, as well as green manure crops, pastures and meadows.

4 | Results and Discussion

4.1 | (Ferrous) Metal Artefacts

For the purposes of a large-scale geophysical survey, the particular focus here is on larger items of ferrous ordnance (i.e., > 10 cm), which includes grapeshot, canister shot, solid shot and howitzer shell fragments (McConnell 1988, pp. 287–332). Such objects are recognized in magnetometry datasets as dipole anomalies (Aspinall, Gaffney, and Schmidt 2008, 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 resolution. Metal detection surveys undertaken with a range of conventional detectors provide a means of verifying the anomalies identified in the larger-scale geophysical surveys. Evidently, these instruments are also capable of detecting a range of small nonferrous conductive targets that are relevant to the archaeology of the battle and not detectable by the large-area methods used here (especially lead ammunition and copper-alloy uniform insignia).

Given the higher sampling density and sensitivity of the magnetometer, the primary focus is on extracting probable ferrous metal findspots from these datasets. A semiautomated method is used to identify these features. First, a kernel with a radius of 30 cm is used to compute focal 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 (2× 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 multipart 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, Gaffney, and Schmidt 2008, p. 69), though the majority are likely ferrous objects. Inevitably, not all of these will relate to the battle, with many likely postdating 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 for further exploration.

A comparison of two survey areas effectively demonstrates this premise. The first (Figure 3) 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). The second (Figure 4) is at the south end, on the outskirts of the village of Plancenoit,

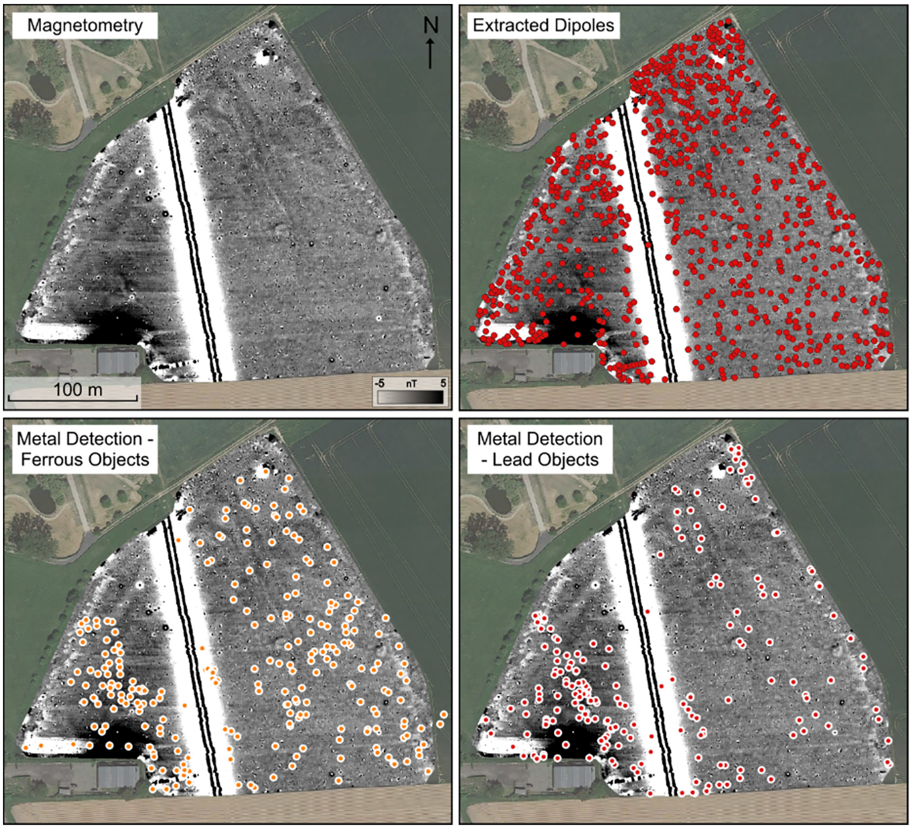

FIGURE 3 | Parcel (ID 179) on the Anglo-Allied reverse slope showing dense concentration of metal objects (858 dipoles in 5.84 ha survey area = 146.9/ha). Compare with Figure 4.

which French and Prussian troops fought for control over. 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).

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 the 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 5). In one, mentioned above and shown in Figure 3, metal detection was undertaken 3 years prior to the geophysical surveys, though both datasets show similarly dense concentrations. In the adjacent eastern 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 magnetometry 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 have been the case on the adjacent field).

Finally, two parcels near the Lion Mound monument, immediately in front of the Anglo-Allied position, appear to show another effect (Figure 6). 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 (Ainslie 2022; Gerrard, Caldwell, and Kennedy 2015). 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 1 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.

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

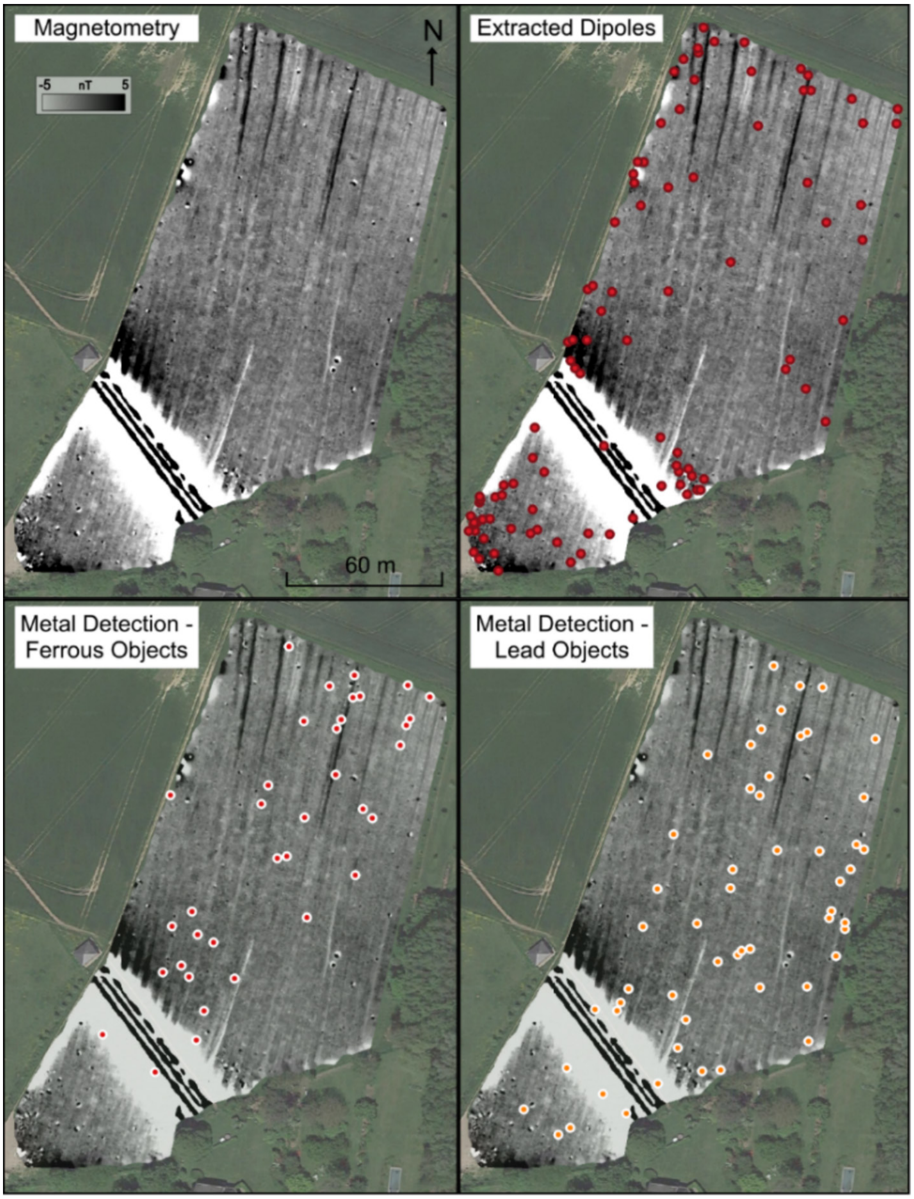

FIGURE 4 | Survey area (parcel 22C) on the outskirts of the village of Plancenoit, showing a relatively sparse concentration of metal objects (96 dipoles in 1.94 ha survey area = 49.5/ha). Compare with Figure 3.

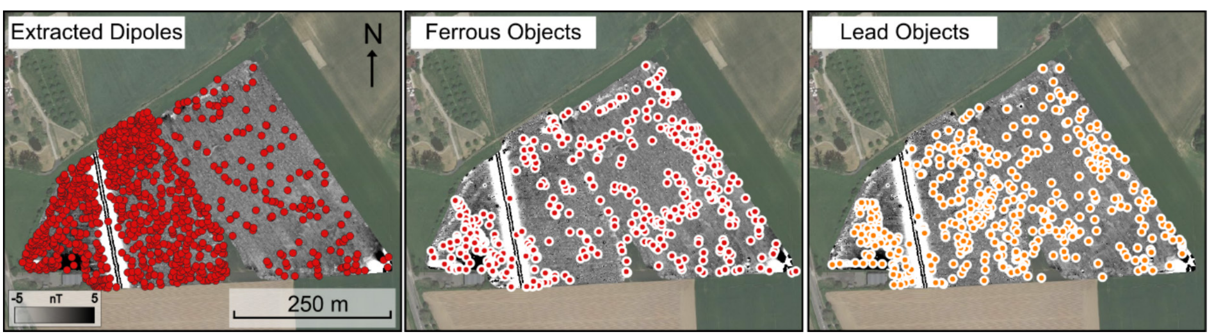

FIGURE 5 | Adjacent survey areas (parcels 178, 179) on the reverse slope near MSJ. The westernmost parcel is the one shown in Figure 3. The metal detection results (centre and right panel) show fairly uniform dense concentrations of metal objects across the two parcels. The easternmost parcel shows significantly fewer dipoles compared to the western one in the magnetometry dataset, as it had been recently metal detected. The western parcel was metal detected 3 years prior to the magnetometry survey.

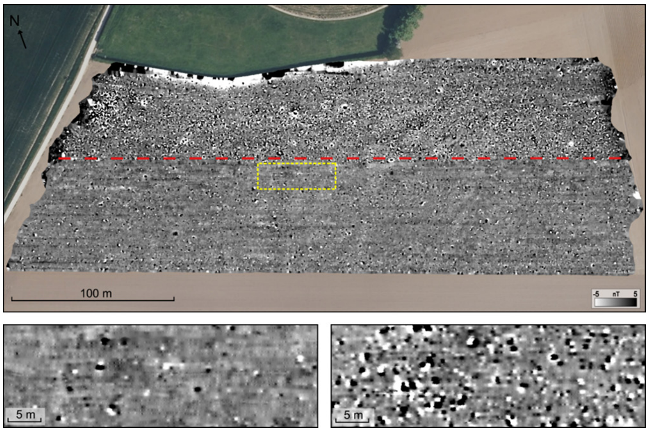

FIGURE 6 | Parcel (17/18) near the Lion Mound (the edge of which is visible at the top of the frame) showing significant differences between two survey periods (autumn 2021 and autumn 2022) in terms of dipole anomalies. At the top, the dashed red line shows the boundary between the two surveys. The insets at the bottom (left 2021 and right 2022) show a detail of the overlapping portion of the surveys (shown in yellow at the top).

correlations between these surveys and metal detection datasets suggest that 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 (primarily lead musket balls) from metal detection datasets. 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.

4.2 | Burials

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. 2015; Bosquet, Yernaux, and Fossion 2014). 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 ferrous metal cartridge pouch liners, 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 (either existing or enlarged/purposefully excavated) at the edge of an existing road and rapidly buried. For the first feature, it was not possible to undertake a 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 magnetometry 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 licence 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.

One explanation for the possible 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, Schäfer, and Pollard 2023). This relates to the use of bone in two industrial processes: manufacture of bonemeal for fertilizer and bone char for refining of sugar. It thus 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 after backfilling and the land converted back to agricultural use, thus homogenizing the upper 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 (unpublished letter in Count Guibert d'Oultremont archives, as cited in Bosquet et al. (2016)). This may also imply that if or when these features were emptied, they would have been subsequently backfilled and ploughed up. In the case of cremation pyres, it is perhaps less likely that the geophysical signature would be wholly erased by ploughing, as a general fire-induced ferrimagnetic enhancement might be expected to still be present. This is, however, strongly dependent on the specific conditions and firing intensity, as it is known that particularly low-temperature firing events (for instance, those generated in charcoal kilns (Powell, Wheeler, and Batt 2012)) render only weak magnetic enhancement that would easily be erased by subsequent landuse (e.g., ploughing). 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. It should be noted that the current dataset does not contradict the absence of burials in the sampled areas; however, the sample size (approximately 10%) is currently insufficient to confirm the absence of surviving burials. Furthermore, only a much smaller subset of the noninvasive dataset has been validated through excavation or borehole sampling.

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, some plough damage was visible, despite its relatively greater depth, and more extensive damage seems to have been avoided only because of a more recent rapidly accumulated 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 (especially in erosion-prone areas), particularly as ploughing depth has increased substantially with the introduction of mechanized agriculture (Van Oost, Govers, and Desmet 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.

4.3 | 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 as originally cited in Chesney (1869, p. 217), 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).

4.4 | Encampments

Some of the surveyed areas are known to be in locations where soldiers were encamped on the night before the battle, based on contemporary maps and accounts (which have been shown to be very accurate based on the recovery of items linked to particular military units (Bosquet and Delpierre 2023)). Recent development-led excavations immediately outside the protected battlefield area uncovered several features interpreted as being related to an Anglo-Allied encampment (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, Brion, and Verbrugge 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 development-led excavation nearby in Wavre (Moulaert, Sosnowska, and Van Driessche 2020), where a battle was fought on the same day.

Definitive evidence for similar pit features and hearths has not yet been found in the geophysical dataset from Waterloo. 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 dugout shelter and cooking structures that often characterize other battlefields. Saturated ground conditions were also 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). Archaeological evidence from immediately outside the study area, however, does confirm that some form of shallowly dug features did exist at Waterloo. 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.

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, and Van Driessche 2020). In some cases, more substantial communal hearths have also been documented at other sites (Authom, Danese, and Denis 2022; Authom and Denis 2022). For the more typical smaller features, however, there is a chance that the 0.5 m crossline 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, it was noted that discriminating their boundaries during excavation was particularly challenging (Danese 2020). These ephemeral features face the same challenges associated with destruction through erosion and intensive ploughing noted above.

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 7A). Other examples relate to concentrations of waste fuel material (clinker, coal, etc.), some of which are very superficial and likely recent (Figure 7C) while others are more deeply buried (Figure 7B). 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.

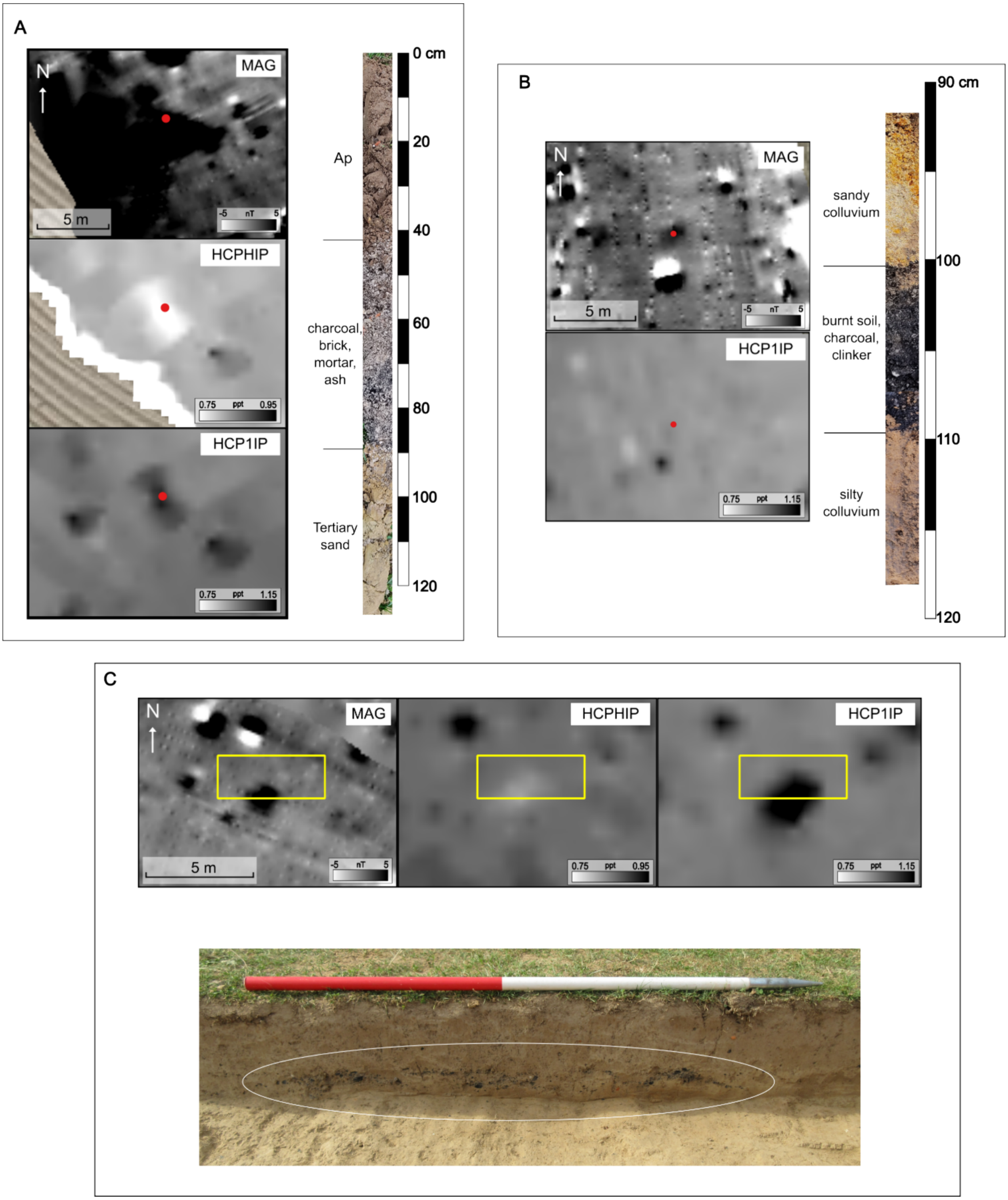

FIGURE 7 | Examples of different discrete magnetic anomalies. (A) Deposit of charcoal and ash with brick/mortar inclusions south of Hougoumont (parcel 66C). The sign change from the 0.5 to 1 m coil pair indicated that the feature would be between 0.3 and 0.6 m below the sensor, confirmed in the borehole (immediately beneath the ploughzone at 0.4 m). (B) Deep lens of burnt soil/slag/clinker near La Belle Alliance (parcel 53A). 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 (parcel 69C). Note the sign change in the shallowest EM coil pairs, as well as the smaller area of the feature in the magnetometry data.

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 8). Its location on the reverse slope at the heart of the Anglo-Allied army 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 2015b), which was linked to a magnetic anomaly from FDEM surveys (Figure 9). 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.

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 70 cm of colluvial overburden. Test excavation revealed an annular feature corresponding to the magnetic anomaly comprised of a thin compact surface of charcoal, slag and hammer scale interpreted as the remains of a small forge (Figure 10). MSa readings of the surface were in the range of 10–45 (10^{-3} SI units [msu]), while the immediately adjacent natural surface was three orders of magnitude lower (ranging from 1 to 2×10^{-5} msu). The feature may relate to the construction of the Lion Mound monument, built a decade after the battle. Contemporary images 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.

Several other anomalies in the same parcel appeared to be good candidates for similar features. They are characterized as

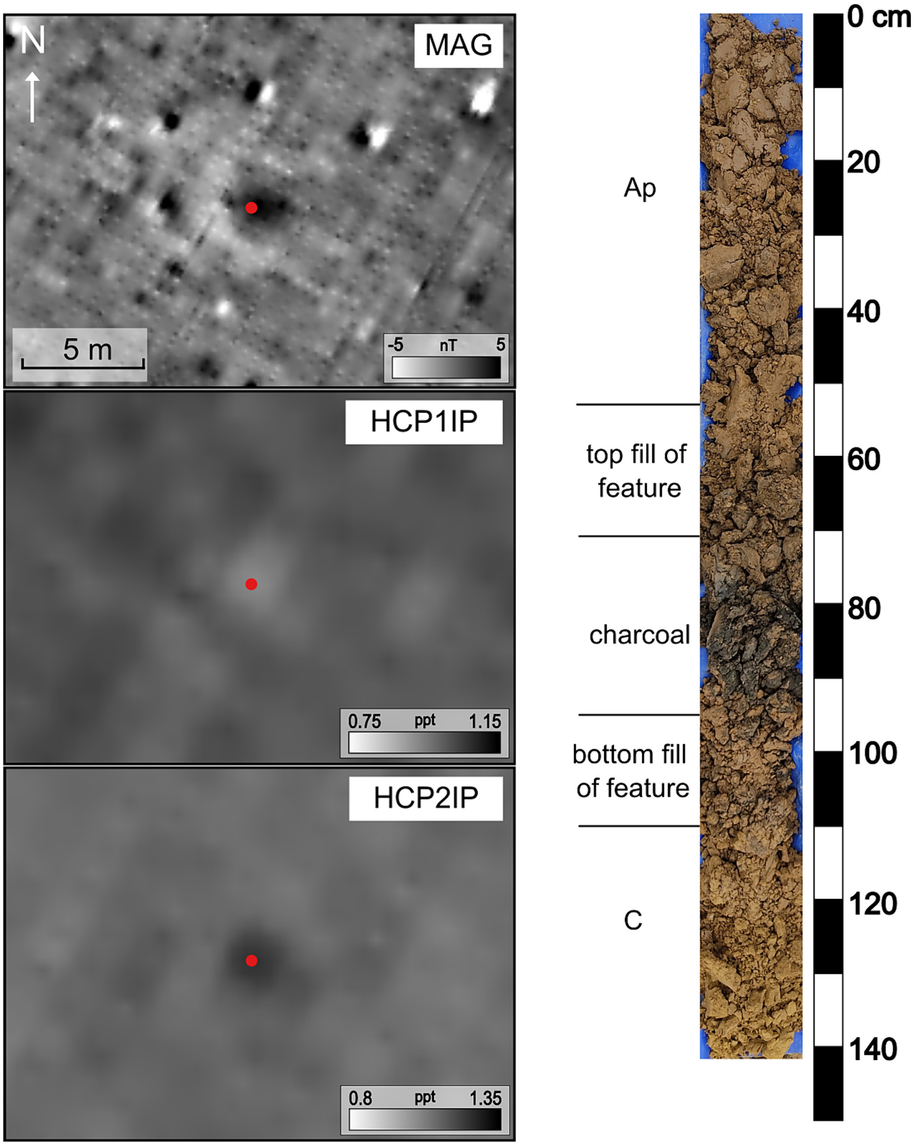

FIGURE 8 | Magnetic anomaly on the Anglo-Allied reverse slope (parcel 39D). The sign change from the 1 to 2 m coil pair indicated that the feature was relatively deep (between 0.6 and 1.2 m). This was confirmed by a borehole which revealed a concentration of organic material and charcoal.

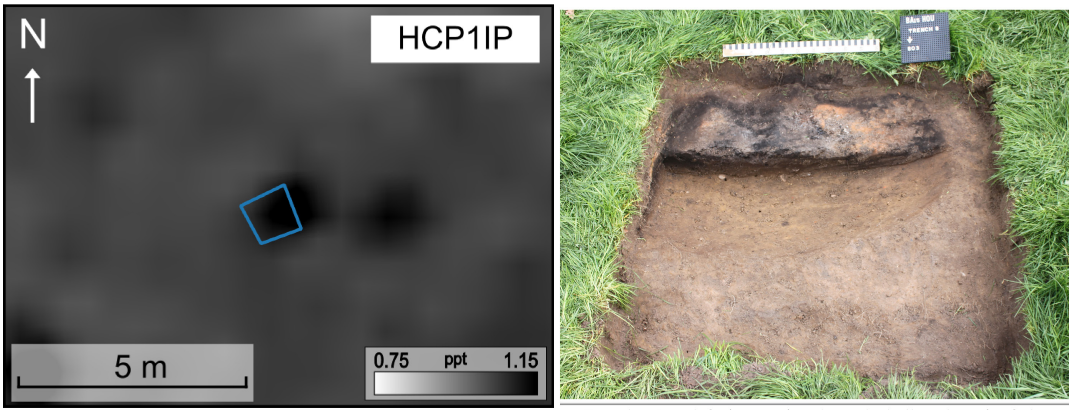

FIGURE 9 | Magnetic anomaly near Hougoumont Farm (parcel 160). The lack of sign change suggested a superficial feature, and a test excavation revealed a very recent hearth related to reenactor activities (Waterloo Uncovered 2015b, p. 23).

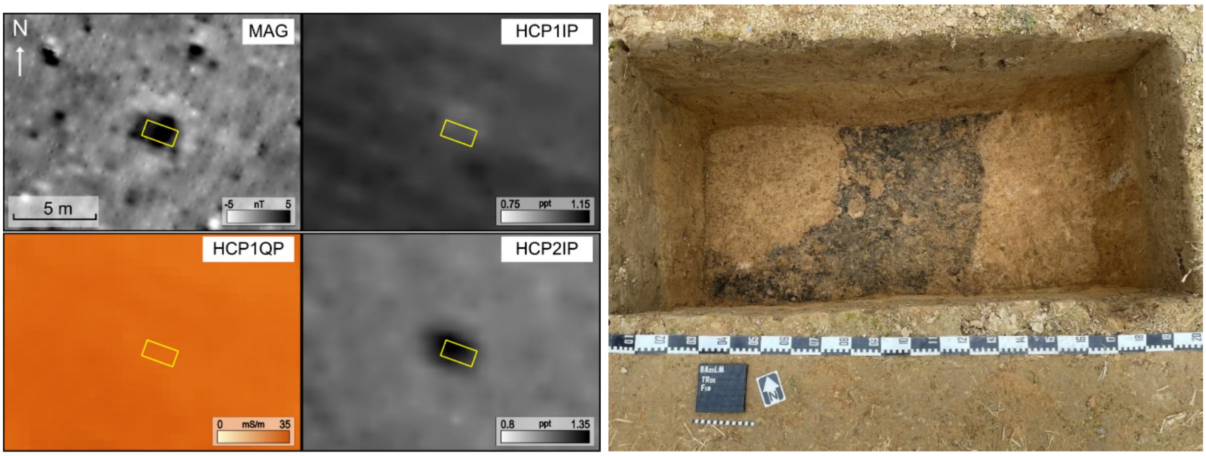

FIGURE 10 | Magnetic anomaly near the Lion Mound (parcel 18). The magnetometer response is moderately strong, and the sign change in the IP data suggested a relatively deep feature, while no contrast was present in the QP response. Test excavations revealed a thin spread of slag, burnt compacted soil and hammer scale.

moderately positive magnetic anomalies (with a sign change in the FDEM IP 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 11). These sandy outcrops have been encountered in various areas across the site where the loess cover is thin or nonexistent. Portions of these units are characterized by gravel-rich deposits containing flint pebbles, sandstones, and iron-rich conglomerates (Laga, Louwye, and Geets 2002; Mees and Langohr 2020; Rommens et al. 2007). These examples illustrate the perils of interpreting all morphologically similar discrete magnetic anomalies as being anthropogenic in origin.

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 12). While these features can sometimes be recognized by their association with significant broader changes in electrical properties (relating to textural differences characterizing Tertiary deposits), their interpretation is seldom straightforward on the basis of sensor data alone.

While the archaeological signatures of typical camp features are now fairly well understood as a result of a recent research focus (Poulain, Brion, and Verbrugge 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.

4.5 | 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.

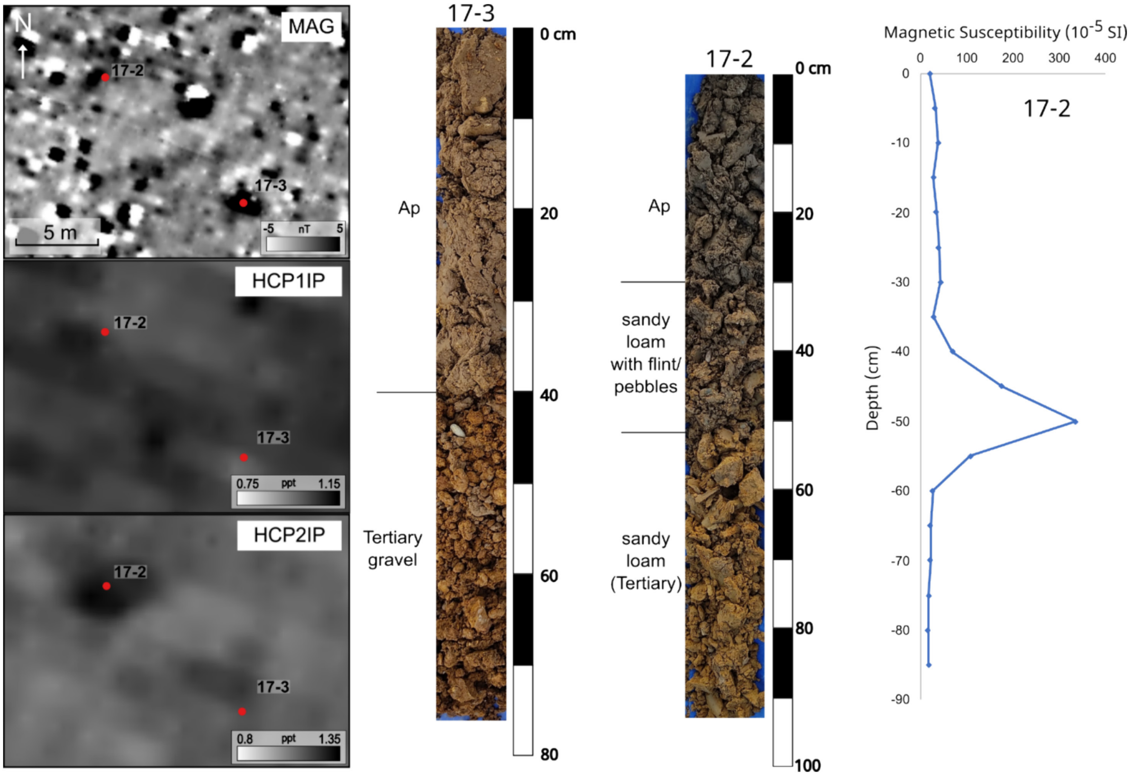

FIGURE 11 | Examples of discrete magnetic features in the same parcel (17/18) as the feature shown in Figure 10, which were revealed to relate to concentrations of iron-rich gravels associated with Tertiary deposits. The magnetic susceptibility log clearly delineates the zone of strong magnetic enhancement.

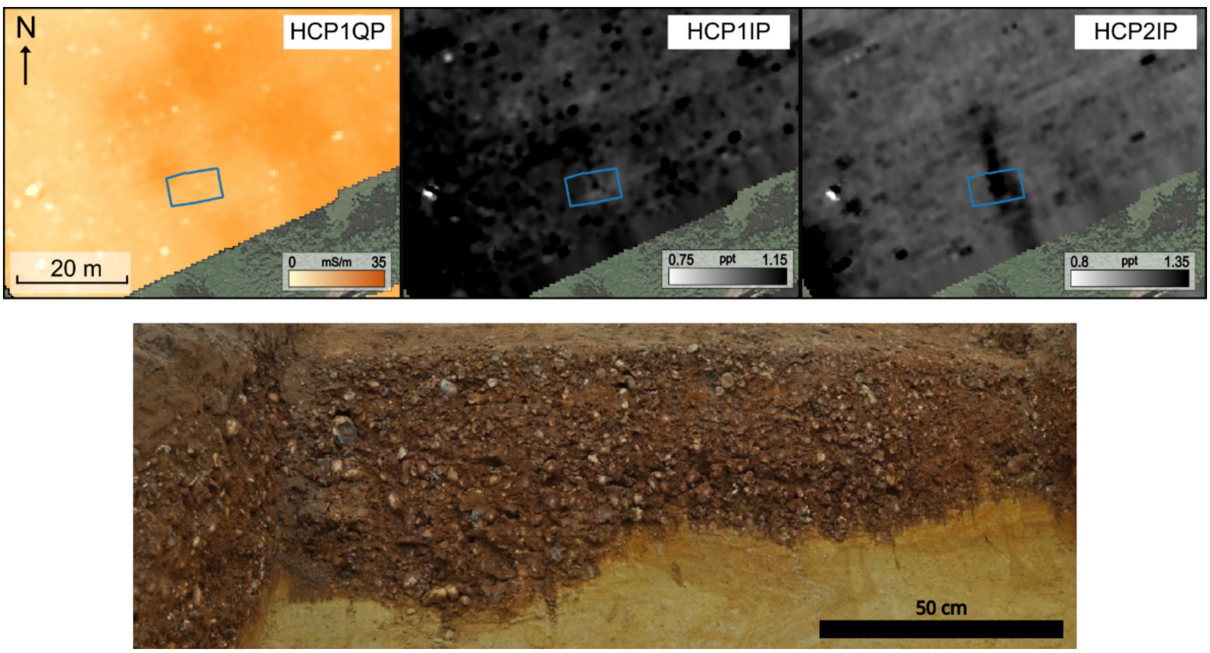

FIGURE 12 | Linear magnetic anomaly near Hougoumont Farm (parcel 160), visible particularly in the deepest coil pair. The electrical contrasts in the broader area suggest an outcrop of Tertiary sand. Test excavations revealed a thick layer of iron-rich pebbles and flints similar to those shown in Figure 11.

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 are well documented in the historical record. The village of Plancenoit played a similar role in the combat between the French and Prussians (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 magnetometry data, terminating at more pronounced anomalies that may be caused by pier or buttress-type features (Figure 13). 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 indicates that it is relatively deep. A test excavation bisecting the eastern section revealed a rubble-filled brick trench without any in situ foundations (Bosquet et al. 2023), indicating that it may have been largely robbed out. A coin dating to 1894 atop this destruction horizon provides a probable *terminus ante 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.

At the farm of Hougoumont on the Anglo-Allied right flank, another sizeable magnetic feature was revealed (Figure 14). The shape of this feature is less distinct (subrectangular, measuring 4 × 5 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 likely in situ foundations. The Ferraris map provides a *terminus ante 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 (if even as a pile of rubble) in the heavy fighting that took place in the wood as the French forces attempted to take Hougoumont.

Another intriguing feature was revealed a mere 50 m to the east of the chapel (Figure 15). A distinct conductive zone measuring approximately 30 × 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 magnetometry 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 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 brickworks field']. The discovery of a brick kiln some 200 m to the northwest (identified in the magnetic datasets (De Smedt 2017)) 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 clearly relating to the battle were found in situ, including musket and pistol balls, lead waste from casting ammunition, grapeshot and a gunflint, indicating that the pit was at least partially open at the time of the battle. With one exception (a pistol ball 60 cm higher), these objects were found at consistent depths with only minimal vertical variability, suggesting that they represent an intact horizon and did not suffer substantial postdepositional movement. It is logical to assume that such a substantial

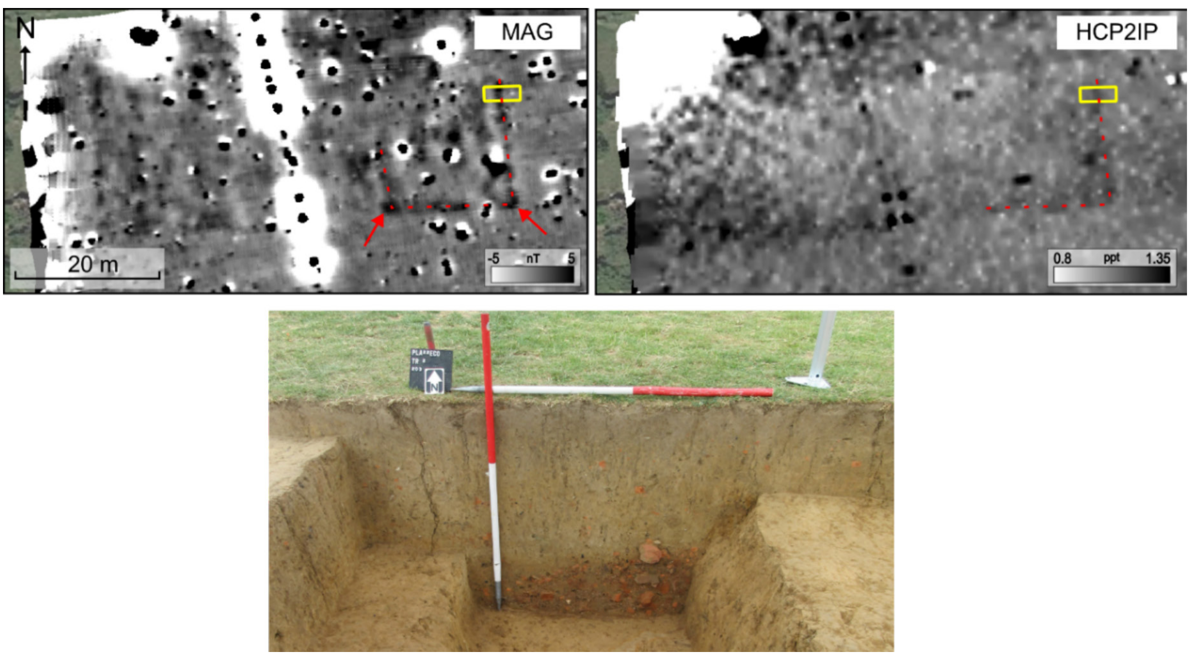

FIGURE 13 | Rectilinear feature (indicated by dashed red line, with arrows indicating possible buttresses at corners) revealed to be remains of a brick structure on the outskirts of the village of Plancenoit (parcel 17K).

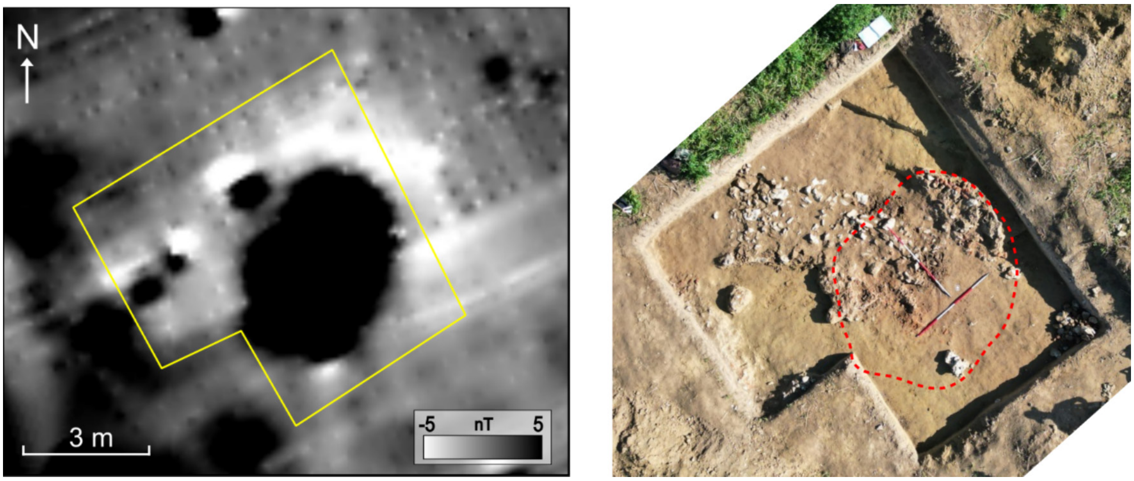

FIGURE 14 | Magnetic feature found south of Hougoumont Farm (parcel 66C) revealed to be remains of a brick structure. The concentration of in situ brick seen in the eastern part of the trench correlates very well with the northern edge of the distinct positive magnetic anomaly (anomaly footprint outlined in red on excavation plan photo). The remainder of the anomaly area indicates the main concentration of brick rubble, documented and removed during excavation.

feature would have played a role in the fierce fighting around Hougoumont, particularly as a means of cover and concealment (Babits 2014). Indeed, re-examination of eyewitness accounts from French infantrymen mentions a '*talus*' ['embankment'] and '*repli de terrain*' ['depression'] at the edge of the wood near Hougoumont, which was used for shelter from Allied fire (Coppens and Courcelle 1999). These accounts may refer to this very feature. Similarly, it could have been a convenient place to dispose of debris, or indeed human remains (as was documented in the 'sandpit' quarry near La Haye Sainte (Pollard 2021)), when undertaking battlefield cleanup, although this has not been documented by the test excavations to date (with the caveat that only 10% of the total area of the feature has been investigated thus far).

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 magnetometry) and resistive (i.e., low conductivity) properties. The test excavation of one such feature revealed a 1 m wide ditch with a depth of at least 65 cm, though it was not possible to uncover its full extent (Figure 16). 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 (Craan) map of the battlefield. 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.

Further north on the reverse slope, a different kind of boundary feature is present with the more typical enhanced magnetic response (Figure 17). 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 EM 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 magnetometry 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 EM 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 120×10^{-5} siu or approximately 2–3× background value). No macroscopic differentiation of the ditch fill was visible in the borehole samples.

4.6 | 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 artefacts/features. This work is described at length elsewhere and is thus not repeated here (Williams et al. Forthcoming). It should, however, be noted that evidence from metal detection

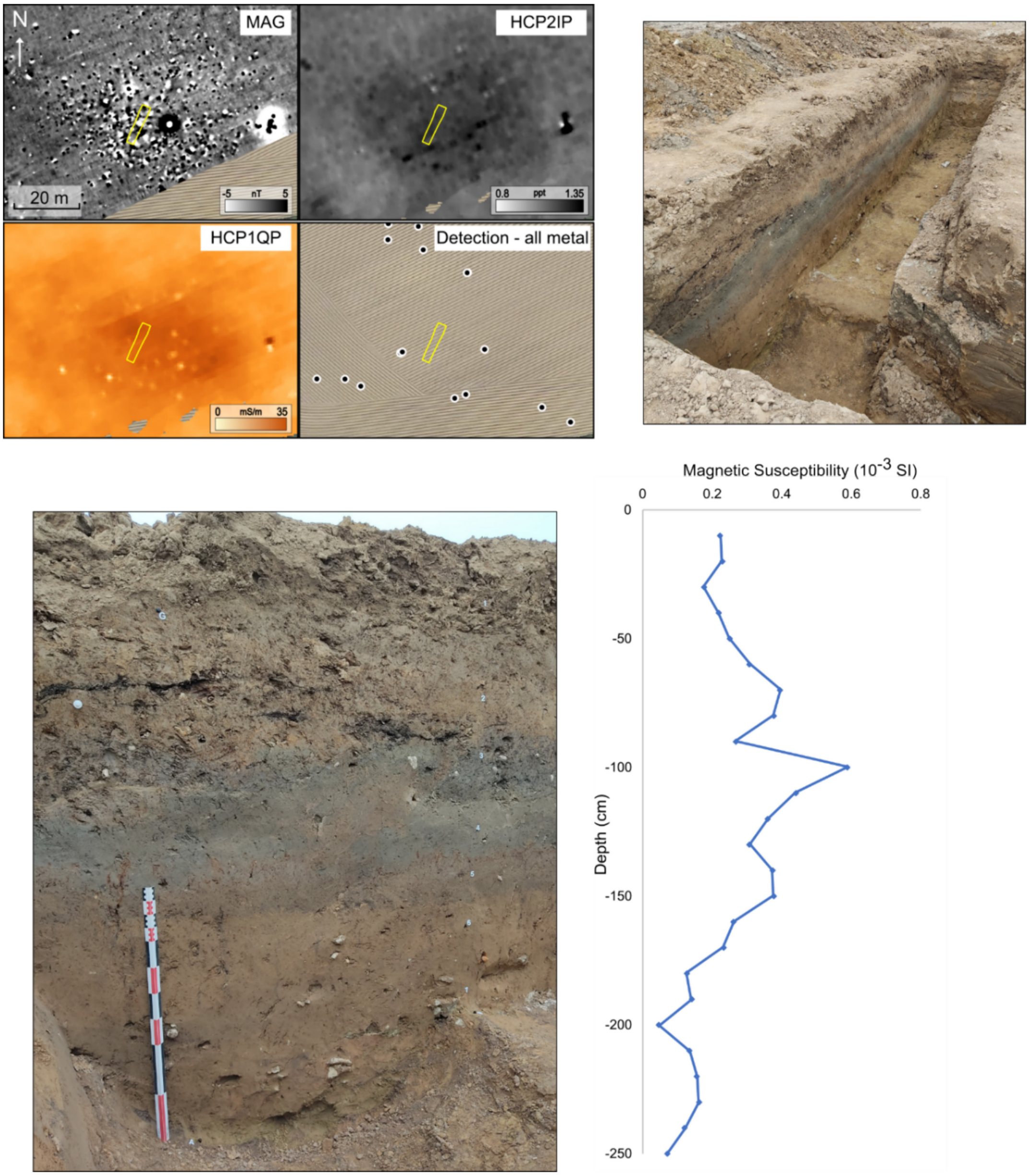

FIGURE 15 | Large feature encountered at the border of a former wooded area near Hougoumont Farm (parcel 66C). Test excavations revealed a substantial pit feature. The susceptibility log shows a peak at a depth of 1 m with the enhancement related to a succession of ploughzones in colluvial deposits.

surveys does seem to indicate that lateral post-depositional artefact movement may be quite limited. Diagnostic artefact distributions are largely in agreement with documentary references, based on historically known positions of troops (Bosquet and Delpierre 2023). Lateral displacement of artefacts may, therefore, be quite limited with vertical displacement from ploughing being more significant. This is in agreement with broader findings in battlefield archaeology (Banks 2020, pp. 199200). Nevertheless, a better understanding of sedimentary processes will permit the explicit testing of these assumptions).

4.7 | 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 magnetometry 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. The presence of 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

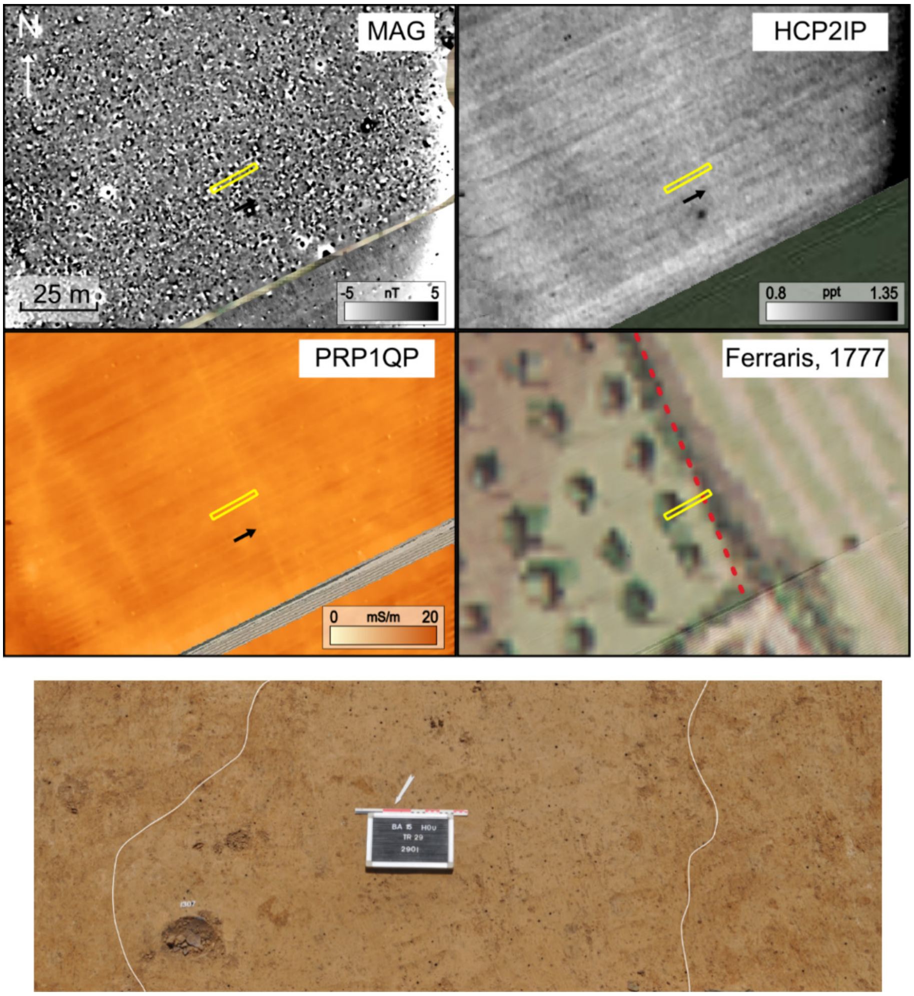

FIGURE 16 | Linear resistive and low magnetic anomaly (indicated by black arrow) revealed to be a ditch after test excavation (trench outline in yellow) (parcel 155B). The feature is most visible in the electrical data and is only faintly apparent in the magnetic datasets (particularly subtle in the magnetometry dataset, which has significant metal clutter). The location of the feature is shown as a dashed red line on the Ferraris map (Cartes de Ferraris 1770–1778, Géoportail de la Wallonie), correlating almost perfectly with the orchard boundary.

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, Passion, and Oldenburg 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 predate 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 cleanup 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, nor the entire battlefield surveyed). Potential reasons for this include historical particularities, insufficient sampling resolution (in the case of particularly small features), lack of contrast, postdepositional influences or a true absence in the sample. 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

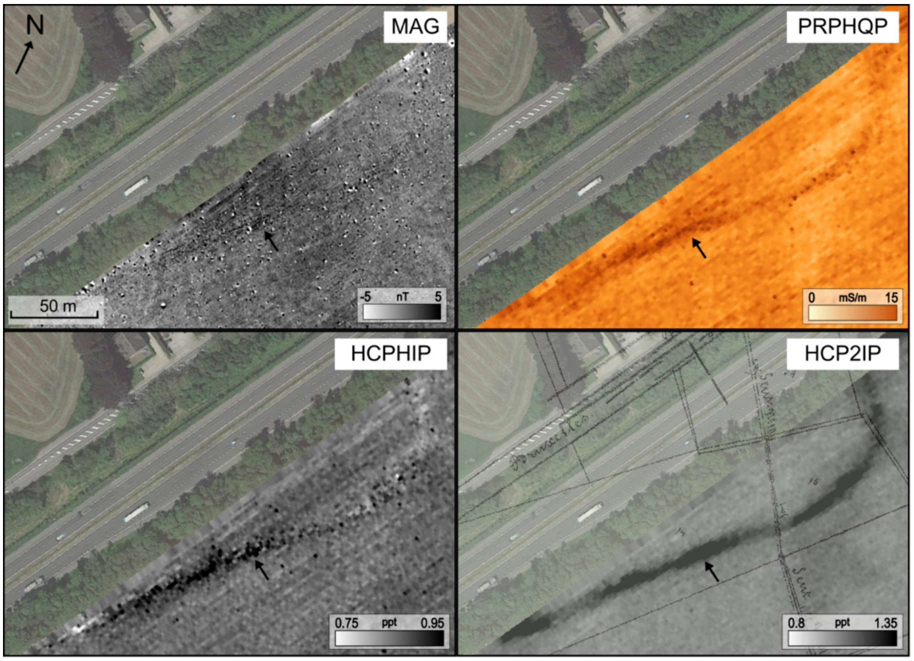

FIGURE 17 | Shallow ditch feature (indicated by arrows) in parcel 39D with a particularly strong response in the 2 m coil HCP coil and a subtler response in the magnetometry data. The shallower coil pairs indicate concentrations of metal in the footprint of the ditch. It appears to match quite closely with a property boundary shown on an 1841 map (Atlas des Voiries Vicinales de 1841, Géoportail de la Wallonie), which is overlaid on the HCP2IP data.

(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 magnetometry 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 multimethod 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 multicoil 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.

We conclude that a 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 are crucial for a more complete understanding of the noninvasive 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. 2022; Stele, Linck, et al. 2023; Stele, Schwickert, and Rass 2021). 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

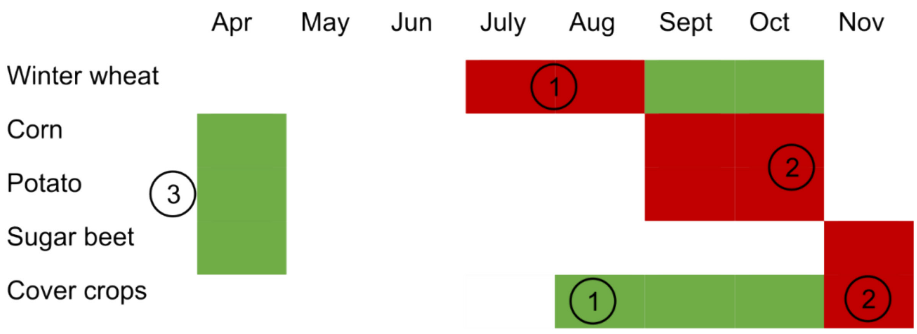

FIGURE 18 | Typical crop cycle calendar for the most common crops in Belgium, with periods of planting/sowing (in green) and harvest (in red) (modified after Gobin 2018, figure 1). In the case of cover crops (e.g., mustard), the crop is not harvested but ploughed into the ground. Numbers correspond to particular survey windows, as outlined above.

in ground-based archaeological prospection with the now routine large-area surveys undertaken by motorized multisensor 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., Aubinet et al. 2009; Leteinturier, Tychon, and Oger 2007; Zhou et al. 2022), it is generally possible to access fields in three main windows (Figure 18): (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)/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. For manual (walking) magnetometry surveys, a rate of 0.5 ha/h was achieved and 0.6 ha/h for 1 m interline FDEM. Thus, approximately 200 additional working days (or 1200 survey hours) would be required to complete the entire 1000 ha area with both methods (assuming motorized configuration and the coarser FDEM sampling interval).

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 drone-deployed geophysical sensors for archaeological surveys (Gavazzi, Reiller, and Munschy 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.

5 | Conclusion

Large-scale geophysical surveys (magnetometry and FDEM) 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 ha 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 noninvasive prospection, ancillary information (historical data), targeted minimally invasive sampling and archaeological excavation 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 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. Our findings suggest that, despite the challenges still to be overcome, large-scale geophysical survey is an essential component of the investigation of battlefield sites.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abbott, D. 2023. "Digging up Waterloo's Secrets." The Brussels Times, 17 June 2023.

Adkin, M. 2001. *The Waterloo Companion: The Complete Guide to History's Most Famous Land Battle*. Mechanicsburg, PA: Stackpole Books.

Ainslie, R. 2022. "Municipal Garden Waste Compost: Its Effect on Magnetometry Results." In *Recent Work in Archaeological Geophysics 2022*, edited by P. Linford and M. Guy, 24–26. London: Near-Surface Geophysics Group.

Aspinall, A., C. Gaffney, and A. Schmidt. 2008. *Magnetometry for Archaeologists*. Lanham: Altamira Press.

Aubinet, M., C. Moureaux, B. Bodson, et al. 2009. "Carbon Sequestration by a Crop Over a 4-Year Sugar Beet/Winter Wheat/Seed Potato/Winter Wheat Rotation Cycle." *Agricultural and Forest Meteorology* 149, no. 3–4: 407–418.

Authom, N., V. Danese, and M. Denis. 2022. "Les campements militaires, un état de la question sur le territoire wallon (Belgique)." In *The Archaeology of Conflicts Early Modern Military Encampments and Material Culture*, edited by M. Poulain, M. Brion, and A. Verbrugge, 79–86. Oxford, UK: BAR Publishing.

Authom, N., and M. Denis. 2022. "Les campements militaires sur le plateau « Belle vue » à Frameries: essai de catégorisation des différents vestiges et interprétation générale." In *The Archaeology of Conflicts Early Modern Military Encampments and Material Culture*, edited by M. Poulain, M. Brion, and A. Verbrugge, 115–129. Oxford, UK: BAR Publishing.

Babits, L. E. 2014. "METT-T, KOCOA, and the Principles of War: A Template Guiding a Better Understanding of Battlefield Behavior and Detritus." In *From These Honored Dead: Historical Archaeology of the American Civil War*, edited by C. R. Geier, D. D. Scott, and L. E. Babits, 263–270. Gainesville: University Press of Florida.

Banks, I. 2020. "Conflict Archaeology." In *The Routledge Handbook of Global Historical Archaeology*, edited by C. E. Orser and A. Zarankin, 192–214. New York: Routledge.

Becker, H. 1995. "From Nanotesla to Picotesla - A New Window for Magnetic Prospecting in Archaeology." *Archaeological Prospection* 2: 217–228.

Becker, H. 2009. "Caesium-Magnetometry for Landscape-Archaeology." In *Seeing the Unseen: Geophysics and Landscape Archaeology*, edited by S. Campana and S. Piro, 129–165. Boca Raton: CRC Press.

Billings, S. D., L. R. Passion, and D. W. Oldenburg. 2002. "UXO Discrimination and Identification Using Magnetometry." *In*: *Symposium on the Application of Geophysics to Engineering and Environmental Problems 2002*. Presented at the Symposium on the Application of Geophysics to Engineering and Environmental Problems 2002, Environment and Engineering Geophysical Society, 12UXO4-12UXO4.

Bosquet, D., C. Barton, S. Eve, et al. 2016. "Waterloo Uncovered July 2016 excavation campaign." Waterloo Uncovered.

Bosquet, D., and P. Delpierre. 2023. "Braine-l'Alleud/Braine-l'Alleud: confrontation des données matérielles et historiques sur le champ de bataille de Waterloo à partir de prospections métalliques." *Chronique de l'archéologie Wallonne* 31: 34–37.

Bosquet, D., V. Moulaert, C. Laforest, et al. 2023. *Waterloo/Waterloo & Lasne/Plancenoit: poursuite des investigations archéologiques du collectif Waterloo Uncovered à la Ferme de Mont-Saint-Jean et à Plancenoit*. Namur: Service public de Wallonie. No. 31.

Bosquet, D., T. Pollard, M. Evans, et al. 2017. *Braine-l'Alleud/Braine-l'Alleud: poursuite des investigations archéologiques sur le domaine d'Hougoumont dans le cadre du projet Waterloo Uncovered*. Namur, Belgium: Agence wallonne du Patrimoine. No. 25.

Bosquet, D., G. Yernaux, and A. Fossion. 2014. *Waterloo/Waterloo: découverte d'un squelette de soldat sur le site de la bataille*. Namur, Belgium: Agence wallonne du Patrimoine. No. 21.

Bosquet, D., G. Yernaux, A. Fossion, and Y. Vanbrabant. 2015. *Le Soldat de Waterloo: Enquête archéologique au coeur du conflit*. Namur: Service public de Wallonie, Département du patrimoine.

Brion, M. 2022. "La recherche archéologique dans les contextes des campements militaires du dix-septième et du dix-huitième siècle en Flandre (Belgique)." In *The Archaeology of Conflicts Early Modern Military Encampments and Material Culture*, edited by M. Poulain, M. Brion, and A. Verbrugge, 67–78. Oxford, UK: BAR Publishing.

Butler, D. K., J. E. Simms, J. S. Furey, and H. H. Bennett. 2012. "Review of Magnetic Modeling for UXO and Applications to Small Items and Close Distances." *Journal of Environmental and Engineering Geophysics* 17, no. 2: 53–73.

Callegary, J. B., T. P. A. Ferré, and R. W. Groom. 2007. "Vertical Spatial Sensitivity and Exploration Depth of Low-Induction-Number Electromagnetic-Induction Instruments." *Vadose Zone Journal* 6, no. 1: 158–167.

Chandler, D. 1980. *Waterloo: The Hundred Days*. Osprey: Osprey.

Chesney, C. C. 1869. *Waterloo Lectures: A Study of the Campaign of 1815*. 2nd ed. London: Longmans, Green, and Co.

Coppens, B., and P. Courcelle. 1999. "Hougoumont: Waterloo 1815." Éditions de la Belle Alliance.

Danese, V. 2020. *Braine-l'Alleud/Braine-l'Alleud: vestiges d'un campement militaire de la bataille de Waterloo*. Namur, Belgium: Agence wallonne du Patrimoine. No. 28.

Darvill, T., F. Lüth, K. Rassmann, A. Fischer, and K. Winkelmann. 2013. "Stonehenge, Wiltshire, UK: High Resolution Geophysical Surveys in the Surrounding Landscape, 2011." *European Journal of Archaeology* 16, no. 1: 63–93.

De Smedt, P. 2013. "Reconstructing Human-Landscape Interactions Through Multi-Receiver Electromagnetic Induction Survey." PhD Thesis. Ghent University.

De Smedt, P. 2017. "Geophysics at Waterloo Uncovered." *In*: *Project Review - Volume 1*. Waterloo Uncovered, 19–22.

De Smedt, P., P. Garwood, H. Chapman, et al. 2022. "Novel Insights Into Prehistoric Land Use at Stonehenge by Combining Electromagnetic and Invasive Methods With a Semi-Automated Interpretation Scheme." *Journal of Archaeological Science* 143: 105557.

Delefortrie, S., P. De Smedt, T. Saey, E. Van De Vijver, and M. Van Meirvenne. 2014. "An Efficient Calibration Procedure for Correction of Drift in EMI Survey Data." *Journal of Applied Geophysics* 110: 115–125.

Evans, M., S. Eve, V. Haverkate-Emmerson, T. Pollard, E. Steinberg, and D. Ulke. 2019. "Waterloo Uncovered: From Discoveries in Conflict Archaeology to Military Veteran Collaboration and Recovery on One of the World's Most Famous Battlefields." In *Historic Landscapes and Mental Well-Being*, edited by T. Darvill. Oxford: Archaeopress Publishing Ltd.

Eve, S., and T. Pollard. 2020. “From the Killing Ground: Digital Approaches to Conflict Archaeology–A Case Study From Waterloo.” *Digital war* 1, no. 1–3: 144–158.

Gaffney, C., and J. A. Gater. 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus.

Gavazzi, B., H. Reiller, and M. Munschy. 2021. “An Integrated Approach for Ground and Drone-Borne Magnetic Surveys and Their Interpretation in Archaeological Prospection.” In *14th International Conference of Archaeological Prospection*, edited by C. Benech, 165–168. Rennes: Université Rennes.

Gerrard, J., L. Caldwell, and A. Kennedy. 2015. “Green Waste and Archaeological Geophysics.” *Archaeological Prospection* 22, no. 2: 139–142.

Glover, G. 2014. *Waterloo: Myth and Reality*. Barnsley, South Yorkshire: Pen & Sword Military.

Gobin, A. 2018. “Weather Related Risks in Belgian Arable Agriculture.” *Agricultural Systems* 159: 225–236.

Laga, P., S. Louwye, and S. Geets. 2002. “Paleogene and Neogene Lithostratigrafic Units (Belgium).” *Geologica Belgica* 4, no. 1–2: 135–152.

Lemaire, F. 2022. “L'organisation des camps de tentes et des camps de baraques dans l'armée française au sortir du dix-huitième siècle.” In *The Archaeology of Conflicts Early Modern Military Encampments and Material Culture*, edited by M. Poulain, M. Brion, and A. Verbrugge, 43–64. Oxford, UK: BAR Publishing.

Leteinturier, B., B. Tychon, and R. Oger. 2007. “Diagnostic agronomique et agro-environnemental des successions culturales en Wallonie (Belgique).” *Biotechnologie, Agronomie, Société et Environnement* 11, no. 1: 27–38.

McConnell, D. 1988. *British Smooth-Bore Artillery: A Technological Study to Support Identification, Acquisition, Restoration, Reproduction, and Interpretation of Artillery at National Historic Parks in Canada*. Ottawa: Environment Canada.

McNeill, J. D. 1980. *Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers*. Mississauga, Ontario: Geonics Limited. No. TN-6.

Mees, F., and R. Langohr. 2020. “Undisturbed Iron Industry Sites in the Sonian Forest, Belgium.” *Journal of Archaeological Science: Reports* 29: 102113.

Moulaert, V., D. Bosquet, O. Collette, et al. 2019. *Braine-l'Alleud/ Braine-l'Alleud, Lasne/Plancenoit et Waterloo/Waterloo: investigations archéologiques dans le cadre du projet Waterloo Uncovered*. Namur, Belgium: Agence wallonne du Patrimoine. No. 27.

Moulaert, V., D. Bosquet, C. Laforest, et al. 2020. *Braine-l'Alleud/ Braine-l'Alleud, Waterloo/Waterloo et Lasne/Lasne-Chapelle-Saint-Lambert: recherches dans les fermes d'Hougoumont, de Mont-Saint-Jean et de Fichermont dans le cadre*. Namur, Belgium: Agence wallonne du Patrimoine. No. 28.

Moulaert, V., P. Sosnowska, and A. Van Driessche. 2020. *Wavre/Wavre: extension du lotissement Matexi au « Champ Sainte-Anne »*. Namur, Belgium: Agence wallonne du Patrimoine. No. 28.

Muir, R. 2000. *Tactics and the Experience of Battle in the Age of Napoleon*. New Haven: Yale University Press.

Muir, R. 2013. *Wellington: Waterloo and the Fortunes of Peace 1814–1852*. New Haven: Yale University Press.

Note, N., W. Gheyle, H. V. den Berghe, et al. 2018. “A New Evaluation Approach of World War One's Devastated Front Zone: A Shell Hole Density Map Based on Historical Aerial Photographs and Validated by Electromagnetic Induction Field Measurements to Link the Metal Shrapnel Phenomenon.” *Geoderma* 310: 257–269.

Note, N., T. Saey, W. Gheyle, et al. 2018. “Evaluation of Fluxgate Magnetometry and Electromagnetic Induction Surveys for Subsurface Characterization of Archaeological Features in World War 1 Battlefields.” *Geoarchaeology* 34, no. 2: 136–148.

Overton, G., and C. Moreland. 2015. *Inside the Metal Detector*. Second ed. Corvallis, Oregon: Geotech Press.

Pollard, T., ed. 2009. *Culloden: The History and Archaeology of the Last Clan Battle*. Barnsley, South Yorkshire: Pen & Sword Military.

Pollard, T. 2021. “‘These Spots of Excavation Tell’: Using Early Visitor Accounts to Map the Missing Graves of Waterloo.” *Journal of Conflict Archaeology* 16, no. 2: 75–113.

Poulain, M., M. Brion, and A. Verbrugge, eds. 2022. *The Archaeology of Conflicts Early Modern Military Encampments and Material Culture*. Oxford, UK: BAR Publishing.

Powell, A. J., J. Wheeler, and C. M. Batt. 2012. “Identifying Archaeological Wood Stack Charcoal Production Sites Using Geophysical Prospection: Magnetic Characteristics From a Modern Wood Stack Charcoal Burn Site.” *Journal of Archaeological Science* 39, no. 5: 1197–1204.

Rommens, T., G. Verstraeten, I. Peeters, et al. 2007. “Reconstruction of Late-Holocene Slope and Dry Valley Sediment Dynamics in a Belgian Loess Environment.” *The Holocene* 17, no. 6: 777–788.

Saey, T., M. Van Meirvenne, M. Dewilde, et al. 2011. “Combining Multiple Signals of an Electromagnetic Induction Sensor to Prospect Land for Metal Objects.” *Near Surface Geophysics* 9, no. 4: 309–318.

Saito, K. 2023. “A Long Walk in the Italian Countryside: Large-Scale Geophysical Survey Within the Emptyscapes Initiative: Examples From the Grosseto-Roselle Valley, South Tuscany, Italy.” *Archaeological Prospection* 30, no. 3: 301–310.

Schmidt, A., P. Linford, N. Linford, et al. 2015. *EAC Guidelines for the use of Geophysics in Archaeology: Questions to Ask and Points to Consider*. Namur, Belgium: No. 2.

Schmidt, V., and J. Coolen. 2021. “Potential and Challenges of UAV-Borne Magnetic Measurements for Archaeological Prospection.” *ArcheoSciences* 45, no. 1: 207–209.

Scott, D. D., and A. P. McFeaters. 2011. “The Archaeology of Historic Battlefields: A History and Theoretical Development in Conflict Archaeology.” *Journal of Archaeological Research* 19, no. 1: 103–132.

Simon, F.-X., G. Hulin, Y. Deberge, and M. Dacko. 2019. “Looking for Military Remains of the Battle of Gergovia: Benefits of a Towed Multi-Frequency EMI Survey.” In *New Global Perspectives on Archaeological Prospection: 13th International Conference on Archaeological Prospection*, edited by J. Bonsall, 47–50. Oxford: Archaeopress Publishing Ltd.

Stele, A., L. Kaub, R. Linck, M. Schikorra, and J. W. E. Fassbinder. 2023. “Drone-Based Magnetometer Prospection for Archaeology.” *Journal of Archaeological Science* 158: 105818.

Stele, A., R. Linck, J. W. E. Fassbinder, and C. A. Rass. 2023. “War Related Impacts (WRI) in Archaeological Magnetometer Data.” In *Advances in On- and Offshore Archaeological Prospection*, edited by T. Wunderlich, H. Hadler, and R. Blankenfeldt, 521–530. Kiel: Universitätsverlag Kiel|Kiel University Publishing.

Stele, A., R. Linck, M. Schikorra, and J. W. E. Fassbinder. 2022. “UAV Magnetometer Survey in Low-Level Flight for Archaeology: Case Study of a Second World War Airfield at Ganacker (Lower Bavaria, Germany).” *Archaeological Prospection* 29, no. 4: 645–650.

Stele, A., M. Schwickert, and C. Rass. 2021. “The Battle of Vossenack Ridge: Exploring Interdisciplinary Approaches for the Detection of U.S. Army Field Positions on a Second World War Battlefield.” *Antiquity* 95, no. 379: 180–197.

Tabbagh, A. 1986a. “What Is the Best Coil Orientation in the Slingram Electromagnetic Prospecting Method?” *Archaeometry* 28, no. 2: 185–196.

Tabbagh, A. 1986b. "Applications and Advantages of the Slingram Electromagnetic Method for Archaeological Prospecting." *Geophysics* 51, no. 3: 576–584.

Trinks, I. 2015. "Advancing Large-Scale High-Resolution Near-Surface Geophysical Prospection." Habilitationsschrift. Vienna University of Technology.

Van Oost, K., G. Govers, and P. Desmet. 2000. "Evaluating the Effects of Changes in Landscape Structure on Soil Erosion by Water and Tillage." *Landscape Ecology* 15, no. 6: 577–589.

Verhegge, J., G. Mendoza Veirana, W. Cornelis, et al. 2021. "Working the Land, Searching the Soil: Developing a Geophysical Framework for Neolithic Land-Use Studies Working the Land, Searching the Soil: Developing a Geophysical Framework for Neolithic Land-Use Studies Project Introduction, –Methodology, and Preliminary Results at 'Valther Tweeling'." *Notae Praehistoricae* 41: 187–197.

Vervust, S. 2016. "Deconstructing the Ferraris Maps (1770–1778): A Study of the Map Production Process and Its Implications for Geometric Accuracy." PhD Thesis. Ghent University, Ghent, Belgium.

Waterloo Uncovered. 2015a. "An Archaeological Evaluation at Hougoumont Farm, Braine -l'Alleud 18th - 31st July 2015." Waterloo Uncovered.

Waterloo Uncovered. 2015b. An Archaeological Evaluation at Hougoumont Farm, Braine -l'Alleud 26th–29th April 2015. Waterloo Uncovered.

Wiewel, A. S., and S. L. De Vore. 2018. "A Fluxgate Gradiometer Survey at an American Civil War Battlefield, Pea Ridge National Military Park." *ISAP News* 53: 1–5.

Wilkin, B., R. Schäfer, and T. Pollard. 2023. "The Real Fate of the Waterloo Fallen. The Exploitation of Bones in 19th Century Belgium." *Belgisch Tijdschrift voor Nieuwste Geschiedenis* LIII, no. 4: 8–30.

Williams, D., K. Welham, S. Eve, and P. De Smedt. 2024. "Geophysical Approaches to the Archaeological Prospection of Early Modern Battlefield Landscapes: A Review of Methods and Objectives." *Journal of Conflict Archaeology* 19, no. 1: 6–41.

Williams, D., K. Welham, S. Eve, and P. De Smedt. Forthcoming. "Minimally-Invasive Approaches to the High-Resolution Mapping of Colluvial Deposits at the Battlefield of Waterloo: Implications for Archaeological Practice.

Zhang, Y., L. Collins, H. Yu, C. E. Baum, and L. Carin. 2003. "Sensing of Unexploded Ordnance With Magnetometer and Induction Data: Theory and Signal Processing." *IEEE Transactions on Geoscience and Remote Sensing* 41, no. 5: 1005–1015.

Zhou, Y., C. Chartin, K. Van Oost, and B. Van Wesemael. 2022. "High-Resolution Soil Organic Carbon Mapping at the Field Scale in Southern Belgium (Wallonia)." *Geoderma* 422: 115929.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.