Revised: 23 July 2018 | Accepted: 12 September 2018
DOI: 10.1002/arp.1725

SPECIAL ISSUE ARTICLE

WILEY

Tales from the outer limits: Archaeological geophysical prospection in lowland peat environments in the British Isles

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Abstract

In order to systematically investigate the potential of conventional near surface geophysical techniques to locate waterlogged archaeological targets in peatlands, the authors applied four conventional geophysical methods – earth resistance, ground-penetrating radar (GPR), magnetic gradiometry and frequency domain electromagnetics (FDEM) – to four lowland peat archaeological test sites in Great Britain. In this article we demonstrate that a Neolithic trackway was identified in the GPR data in Somerset, with likely 'proxy' detections of chemical changes showing up in both electrical and magnetic surveys. This was determined by a coring programme and inductively coupled plasma optical emission spectrometry (ICP-OES) multi-element analysis of peat samples to determine the relative concentrations of geophysically relevant chemical elements. Though no Bronze Age timbers were detected at Flag Fen, a post-Bronze Age agricultural landscape was identified in both the GPR and gradiometer surveys. We conclude that GPR has the greatest potential for archaeological geophysical prospection in peatland environments, but that electrical and magnetic methods can usefully be employed as secondary sources of information and should not be discounted from future research. Further, this article argues that better understandings must be developed of the impacts of geochemistry on geophysical data if we are going to realistically pursue 'whole landscape' surveys.

KEYWORDS

frequency domain electromagnetics, GPR, gradiometry, peatland, resistivity, wetland

1 | INTRODUCTION

Peatland sites are important to archaeologists because of the preservation of organic material such as wood, textiles and leather, which are not usually recovered from more typical 'dryland' sites. The physical and chemical conditions in their waterlogged soils create a remarkable preservation environment. The impact of peat, and other wetland sites on our understanding of the past should not be underestimated. This is particularly true for the prehistoric period in north-western Europe (Coles, 1987, 1996; Coles, 1990, 1991; Olivier & van de Noort, 2002; van de Noort, 2002; van de Noort, Fletcher, Thomas, Carstairs, & Patrick, 2002). The specific properties that make them so valuable to our discipline also make them very difficult to detect by conventional survey methods, and have in part protected them from 'antiquarian' attentions. Due to their depth of burial and the waterlogged nature of the soils, peatland sites rarely show up in aerial or topographic surveys. They frequently only come to light whilst being destroyed, either by active peat removal or due to development, drainage or desiccation. Furthermore, the preservation environments are often fragile, with small disturbances causing the rapid loss of artefacts and environmental information, which may not be apparent at the surface (Boreham et al., 2011; Pryor, 2001). Ideally, we need a non-invasive technique for the identification and monitoring of peatland sites that would allow them to be identified and protected prior to damage being caused.

In non-peat environments, geophysical prospection is routinely used to this end, having over the last decade being incorporated into the identification and protection of archaeological remains in a wide variety of landscapes, from urban areas to deserts and the sea floor. Geophysical methods are also employed in the quantification and classification of peatlands (for geotechnical and environmental/ecological reasons and in order to quantify them as a resource for fuel) (Slater & Reeve, 2002; Trafford & Long, 2016). This is usually done in combination with coring and laboratory testing. Classification systems also vary between disciplines, countries and purpose, being intensely pragmatic. For example, ecologists emphasize the trophic qualities or perhaps the landscape that produced the peat deposit, whereas engineers are more interested in shear strengths; these properties are interrelated in complicated ways (Gore, 1983, 27–29). Prospection for archaeological targets within and below peat has however remained difficult. The first guidelines issued by English Heritage in the UK in 1995 were pessimistic, stating that '*geophysical techniques can, as yet, have little part to play in wetland evaluation. Structural remains (such as pile dwellings, trackways etc) in organic sediments, in particular, are undetectable*' (David, 1995, 12, emphasis in original). By 2008, and the start of the research project under discussion, the situation had changed slightly, with an acknowledgement of the success of ground-penetrating radar (GPR) in very particular circumstances and a call for further research and ground-truth (English Heritage, 2008, 16–17). Our approach (Armstrong, 2010) therefore involved case studies on peatland sites in the UK with known archaeology, using four well accepted and understood techniques: magnetic gradiometry, earth resistance, GPR and frequency domain electromagnetic (FDEM) surveys. These sites were selected as relatively well-understood examples of wetland archaeological sites, which can be seen as comparable to other potential wetland sites involving structures buried in peat. Where possible, the results of the surveys were validated through small test excavations or corings. Here, we report on the lowland peat sites examined; Flag Fen in East Anglia and the Sweet Track in the Somerset Levels.

2 | CASE STUDIES – INTRODUCTION

Both Flag Fen (Cambridgeshire) and the Sweet Track (Somerset) are prehistoric monuments, dating to the Bronze Age and the Neolithic, respectively. They are the most studied and therefore best-understood peatland sites in the UK (see Figure 1 for location, and Table 1 for information about the sites and their landscape setting).

At the Sweet Track, a Neolithic trackway of unique construction, two areas of supposed trackway were selected to test the ability of the various techniques to locate the timber trackway and any associated structures. One was in a 'restored' peat bog (hereafter called the Canada Farm site), where the location and depth of the trackway

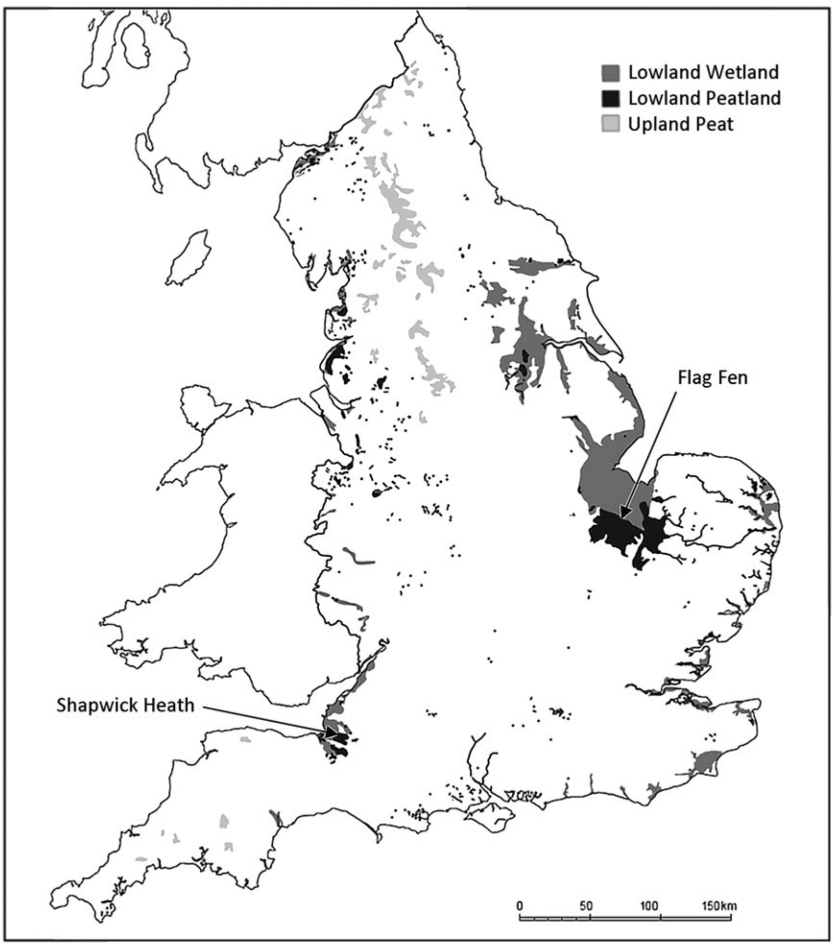

FIGURE 1 Site locations and English peatlands, after van de Noort et al., (2002, Figure 1)

TABLE 1 Geology and geophysical targets

Site	Geology	Peat type	Depth of timber remains	Dimensions of timber remains
Sweet track peat works	Blue estuarine clays	Phragmites, wood and raised bog	0.75 m	0.5–1 m wide and deep
Sweet track Canada farm	Blue estuarine clays	Phragmites, wood and raised bog (now desiccated in upper parts)	0.75 m	0.5–1 m wide and deep
Flag fen platform (area 1)	Oxford clay	Freshwater and phragmites peats, alluvium interleaved	As above	Platform; survey should cover edge of this structure
Flag fen causeway (area 2)	Oxford clay	Freshwater and phragmites peats, alluvium interleaved	Unclear, 'within' 1.5 of surface based on previous excavations	10–15 m wide arrangement of large timbers in up to five rows, largely upright

Peat Types: Phragmites: organic matter is mostly phragmites reeds, formed in lacustrine environments. Freshwater peats: lacustrine peat not dominated by phragmites. Wood peat: peat largely of woody material, formed under carr vegetation. Raised bog: peat formed in raised mire conditions from sphagnum, other mosses and cotton grass. They have differing trophic contents, organic/mineral ratios, pH values and moisture capacity.

was known from evaluation trenches in the 1990s (Coles, 1996), summarized in Table 1. This was also close to an area that had previously been examined with GPR, which had apparently succeeded in identifying the trackway (Utsi, 2007; Utsi Electronics, 2001). A second area was surveyed where it was thought the trackway made landfall on a sandbar known locally as Shapwick Burtle (hereafter referred to as The Old Peat Works site), which stands at least 2 m above the current local relief. This may have been occupied in prehistoric times, based on anecdotal reports of worked flint being cast up from rabbit burrows (see Figure 2 – areas surveyed at the Sweet Track).

Flag Fen is a Bronze Age site consisting of a somewhat enigmatic large timber platform constructed in a wet part of the landscape, with a large post row or palisade linking it to dry land to the north and south, as summarized in Table 1. It has been interpreted as a ritual place in the landscape (Pryor, 2001, 10). There are later remains at the site, and earlier ones. These include a Roman causeway on roughly the same alignment as the post rows, and Neolithic funerary monuments on the fen-edge, as well as traces of agricultural landscapes from the Neolithic and Bronze Age (French, 2003; Pryor, 2001, 2005). Here, one group of surveys was conducted over one edge of the platform and the Roman causeway, and another over

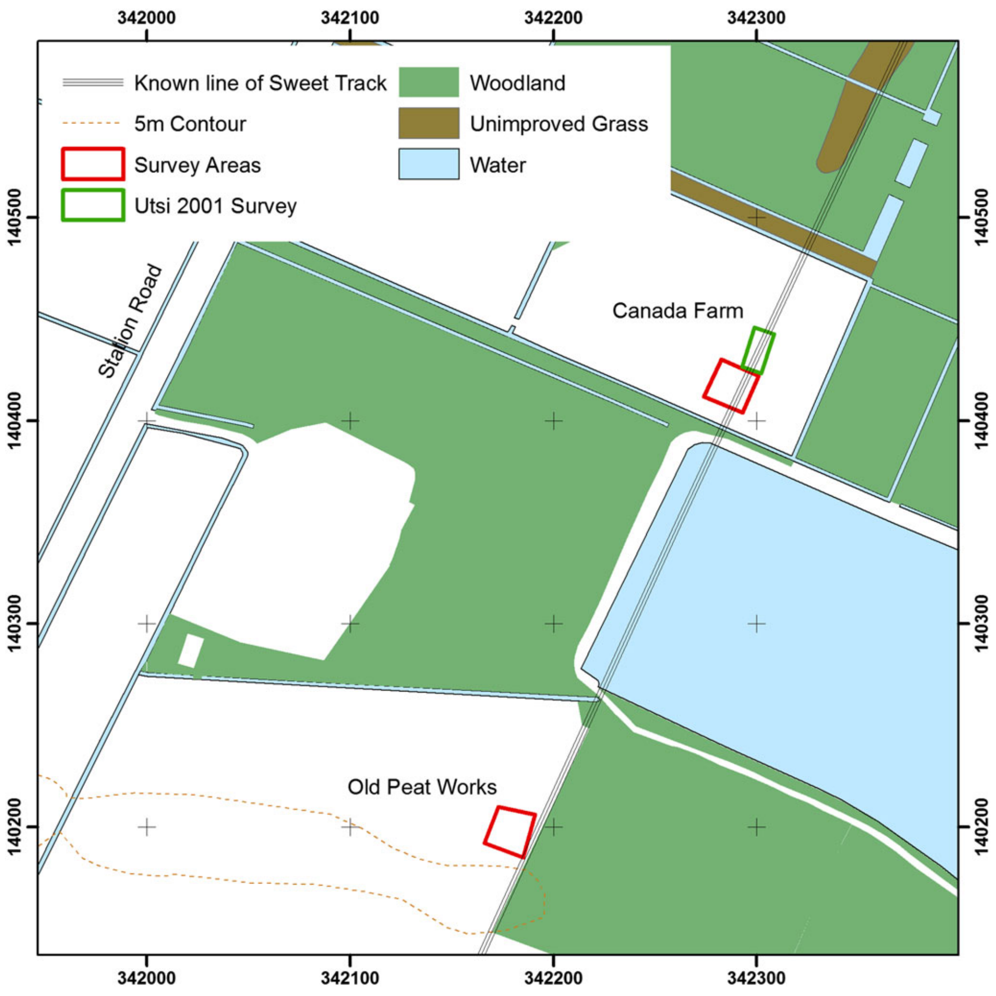

FIGURE 2 Sweet track survey areas, expected archaeology and previous survey [Colour figure can be viewed at wileyonlinelibrary.com]

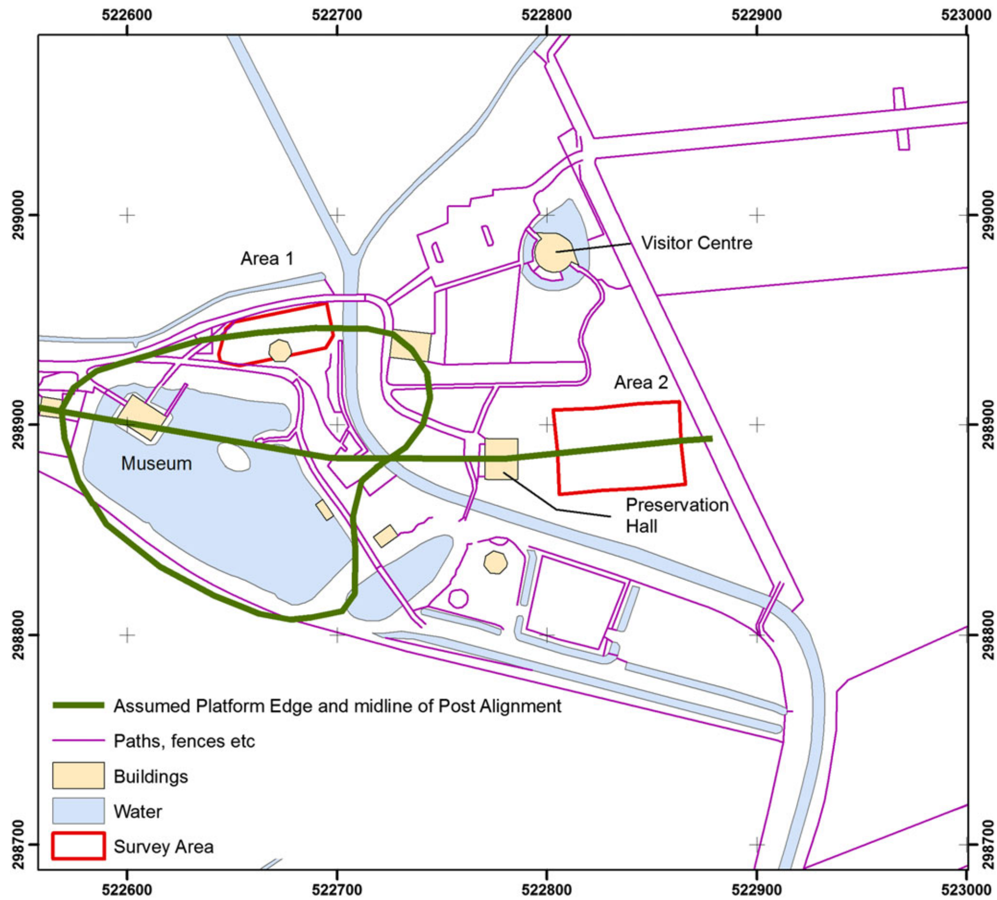

FIGURE 3 Flag fen survey areas and expected archaeology [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Combined tables of instruments and methods from case studies

Method	Instrument	Traverse interval	Measurement interval	Traverse method	Other settings
Earth resistance	RM15 with MPX15 (Geoscan research)	1 m	1 m (six readings at each point covering 0.25–1.5 probe separation)	Zig-Zag (preserving the array geometry)	0.5 Ω resolution
Magnetic gradiometry	FM36 (CF, PW, FF2) DualGrad601 (FF1)	0.5 m 0.5	0.5 m 0.125	Parallel Parallel	0.1 nT resolution 0.1 nT resolution
GPR (MalaRAMAC)	250 MHz	0.5	0.05 m	Zig-Zag (CF, PW, FF2), parallel (FF1)	CF and PW: 65 ns time window, 580 samples, presumed velocity 0.08 ms. FF1: 128 ns time window, 520 samples, 0.08 m/s velocity. FF2: 128 ns time window, 250 samples, 0.07 m/s velocity
	500 MHz	0.5 m	0.05 m	Zig-Zag (FF1, FF2)	CF and PW: Test lines only. FF1: 49.2 ns time window, 512 samples, 0.08 m/s velocity. FF2: 31 ns time window, 512 samples
FDEM	EM38B (Geonics)	1 m	1 m	Zig-Zag	In and quadrature phases logged simultaneously using manual trigger, at ground surface, in horizontal (CF and PW) and vertical magnetic dipole orientations (all sites)

Note: Site abbreviations for variant settings: CF, Canada Farm; PW, Peat Works; FF1, Flag Fen Area 1; FF2, Flag Fen Area 2.

the whole width of the post alignment (see Figure 3 – areas surveyed at Flag Fen).

In all four cases, the aims were to detect any archaeological remains present and to make comparisons between the four techniques employed in relation to how well they were able to identify and describe archaeological anomalies. The exact equipment, settings and survey resolutions employed are shown in Table 2. Though by current practice, 0.5 m line spacing for the 500 MHz GPR survey is 'sparse', this was a deliberate decision, in order to have the same centre-line for the two different antennae employed. We recognize this

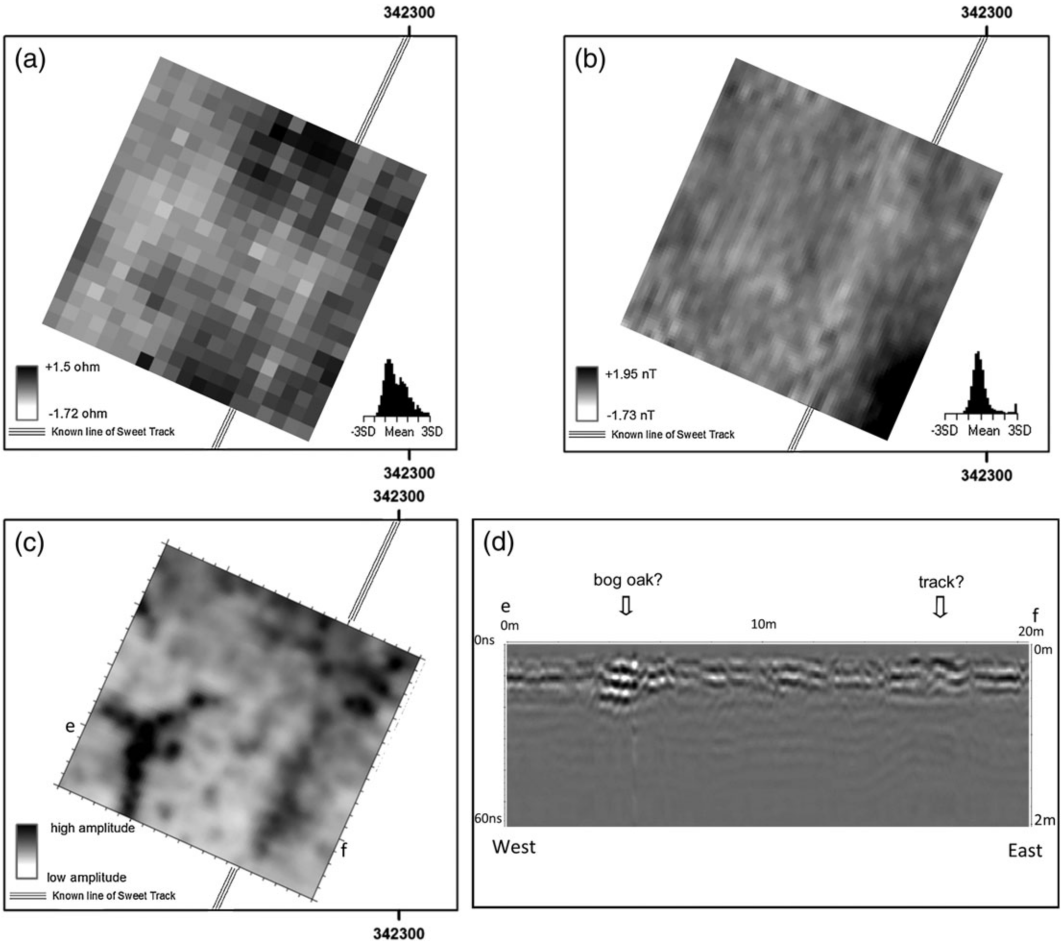

FIGURE 4 (a) 0.75 m probe separation earth resistance data (processed, high passed), Canada farm, (b) processed magnetic gradiometer data, Canada farm, (c) 250 MHz ground-penetrating radar (GPR) timeslice at 14–17 ns, Canada farm, (d) 250 MHz radar profile taken in the ***y*** direction at 15.25 m on the ***x*** axis of the grid at Canada farm, background removed and linear gain applied

means the 500 MHz datasets are less detailed and thus the interpretation less certain as a result.

2.1 | Geophysical results: Sweet track

At Canada Farm, traverses were made perpendicular to the known trackway and a clear linear anomaly was detected at its predicted location, with the exception of the FDEM data (Figure 4). The conductivity response of the FDEM survey did however corroborate a clear electrical conductivity gradient also seen in the inversions of the multiplexed electrical resistance data. The magnetic results showed a negative linear anomaly (compared to the background), which was of the order less than 1n*T* (Figure 4(A)), somewhat offset from the low resistance linear anomaly observed most clearly in the 0.75 m probe separation electrical resistivity data (Figure 4(B)). The clearest anomaly in the GPR data was a large dendritic anomaly to the west of the trackway, which we have interpreted as a bog oak. The validation cores however just missed this anomaly (see later), and so this interpretation is supposition based on the anomaly morphology and the presence of bog oaks appearing at the ground surface near to the Peat Works survey area. There was also a series of consistent responses in the expected location of the track, in slices 11–16, or estimated depth of 44 to 76 cm below the surface (Figure 4(C)). This also shows in the GPR profiles, such as the one collected at 15.25 m on the *x* axis of the grid (Figure 4(D)), as indicated with a line in Figure 4(C). The reflection that is part of the linear anomaly is indicated by the arrow in Figure 4(D). Taking the very strong anomaly interpreted as a bog oak in the GPR, missing from all of the other datasets, along with what is known about waterlogged soil conditions and environmental magnetism (Thompson & Oldfield, 1986), we can discount the resistivity and magnetic results as direct detections of anomalous responses arising from the trackway timbers, and instead suggest they are ‘proxy’ detections arising from changes in the peat composition at the position of the track, caused by it. We suggest this originates in its effect on the hydrology or the composition of the peat perhaps due to a damming effect caused by the trackway's timbers. Finally, although the anomalies were clear to us, they would perhaps not be so easy to pick out in a large dataset acquired for prospection purposes. We see the anomalies because we expect them and so this may be a case of confirmation bias, lying as they do at the borderline of detectability.

At the Peat Works, no sign of the trackway could be identified. It is possible that the recorded position of the trackway in this field is incorrect; there is some debate about whether it continues this far south. It is also possible that the peat in this area has desiccated so much that there are no longer any timbers present; this field has a number of emerging bog oaks, due to peat shrinkage, and is dry enough to be used as regular

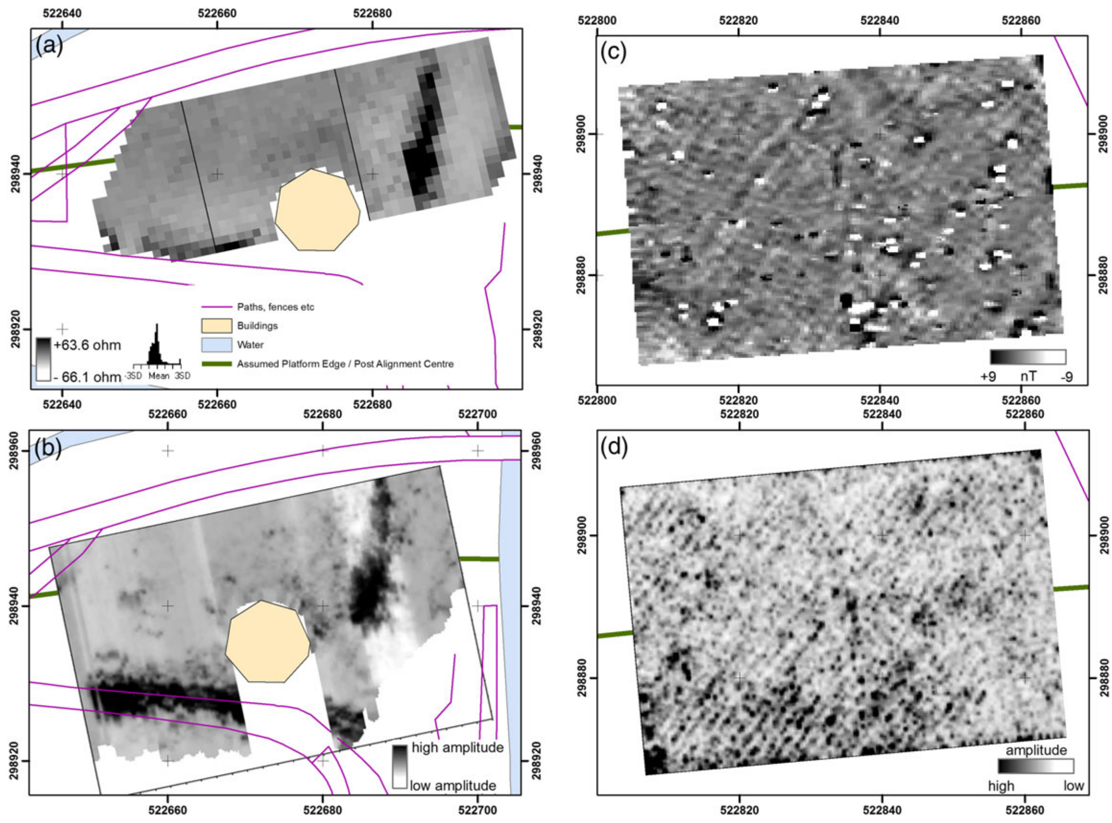

FIGURE 5 Flag fen results: (a) 0.5 m probe a: 0.5 m probe separation earth resistance data (processed, high passed), flag fen area 1, (b) 250 MHz ground-penetrating radar (GPR) timeslice at 11–16 ns, flag fen area 1, (c) processed magnetic gradiometer data, flag fen area 2, (d) 250 MHz GPR timeslice at 20–26 ns, flag fen area 2 [Colour figure can be viewed at wileyonlinelibrary.com]

pasture. The probable bog oak at Canada Farm was detected at roughly the same depth as the trackway; if the eroding bog oaks here are in the same relative position to the track, it may have been lost to dessication.

2.2 | Geophysical results: Flag fen

At Flag Fen, the first surveys searched for the edge of the platform (Figure 5(A, B)). The results identified the Roman causeway (showing as a high resistance/high amplitude anomaly in the resistivity and GPR data, see Figure 5(A, B)) and a previously unknown offshoot, and helped re-locate a former excavation trench, but the surveys did not locate the timbers or any sign of the edge of the platform area. We conclude that this is caused by a combination of circumstances. The surface was very dry at the time of the surveys, which created high contact resistances and a lot of reflections in the GPR due to deep cracks. Coring revealed a complex deposit sequence (Armstrong, 2010, 549) and the edge of the platform is likely to be a gradual, rather than abrupt, transition from all timber to all peat.

The situation in Area 2 was very similar. Surface cracking, abrupt changes in moisture content, and complex interleaving of sediments (confirmed by coring) obscured the timbers from all of the surveys; we simply could not get sufficient signal-to-noise ratio in the GPR data at the required depth. However, the results of the gradiometer (Figure 5(C)) and the 250 MHz GPR (Figure 5(D)) surveys revealed two different archaeological ploughing regimes that as yet have not been recognized in excavations, adding to the landscape history of the site.

What was also a useful, but unintended result was that the resistivity data was of great interest to the site archaeology team, as it showed which areas were the most dried out, with all of the attached risks to the preservation of the organic archaeological remains. They were able to use this information to change plans for planting trees on some parts of the site.

3 | VALIDATION AND DISCUSSION

With such sensitive landscapes and archaeology, excavations and coring to assess the geophysical results needed to be conducted very carefully. The principles we adopted were that each intervention should be the minimum necessary to answer specific questions. This meant that we focused on coring to confirm the physical composition of anomalies and to collect samples of peat and soils for analysis.

3.1 | Canada farm

At the Sweet Track, the validation effort focused on the Canada Farm site. The responses at the Peat Works were too ephemeral, and not connected with the timber causeway, to warrant further work. Following our conclusion that the gradiometer and resistance anomalies were proxies for the trackway, rather than the track itself, we sought a mechanism by which this could happen. The site seemed to be uniformly wet, with surface water present over much of the area. There is no reason why a difference in moisture content might produce a gradiometer anomaly, so we instead investigated the possibility that there could be a chemical difference (in the pore water, or the peat, or perhaps in the timbers of the trackway) that affected both the magnetic gradiometry and the resistivity. We hypothesized that the trackway might be lying at a right angle to the hydraulic gradient in the peat, interrupting it and causing certain substances to precipitate out and accumulate in the vicinity of the trackway. It was well beyond the scope of the research project to investigate the exact hydraulic and chemical processes involved; instead, we decided to search for spatial variations in the relative amounts of trace elements. If there were spatial variations that corresponded to the geophysical anomalies, then we could infer a link.

We carried out a transect of ten gouge-auger cores at 2 m intervals across the geophysical grid in the same direction as the observed gradient to characterize the sequence of peat deposits and look for changes that might help interpret the geophysical data (Figure 6(B)). These were stopped when we hit the blue clay layer at about 2.5 m below current ground level. We also obtained four 1 m Russian peat-auger cores across the site on the same line as the gouge transect, with two to either side of the grid orthogonal to this. These were sub-sampled to 10 cm sections and used for the particle size, organic matter and chemical investigations. A small 1 m × 2 m inspection trench was placed over the linear anomaly identified in the GPR data (Figure 6(B, C)). This did not reveal any diagnostic structural elements of the trackway but there were a series of timbers lying parallel to one-another at 0.45 m below ground level, on a horizon within the peat about 20 cm higher up the profile than excavation records suggested we should expect the trackway, but in the depth region of the anomalies in the GPR data. This time/depth conversion was made using estimated radar velocities suggested by Utsi (2003, 2004, 2007), and though the discrepancy between the expected and predicted depth was concerning during the initial interpretation, the velocity estimates were vindicated by the excavation. The timbers were carefully lifted and the trench was continued to a depth of 1 m as this took us well past the 0.8 m depth of the trackway documented in previous excavations: no further timbers were located. Richard Brunning, the Levels Archaeologist, present during the original excavations, was also present at our excavation and remarked that the timbers recovered looked like the offcuts and construction debris encountered at times during the original excavations of the trackway. We obtained a 1 m peat monolith sample in the line of the other Russian peat-auger corings from the side of the trench before it was closed (Figure 6(B, C)).

The cores were then analysed at Bournemouth University. For the particle size determinations the pipette method was followed, and the organic matter and water contents (mass based) were assessed using a standard loss-on-ignition method (Avery & Bascomb, 1982). For the trace element analysis, wet peat samples were digested using a nitric acid process (rather than aqua regia, in an attempt to recover more iron) and then presented for inductively coupled plasma optical emission spectrometry (ICP-OES) using two Fisher Scientific multi-element standards for calibration (giving a suite of 30 elements), and certified reference material NWRI TH-2 for cross-checks. Three repeats of each test were performed; the results presented are based on the averages from those. With the technique used it was not possible to speciate the elements, which means we were unable to determine the particular forms of iron oxides present.

The linear high amplitude reflections in the GPR timeslices starting at 0.44 m (see Figure 4(C)) deep were interpreted as being caused by the timbers encountered in the excavation, or their direct

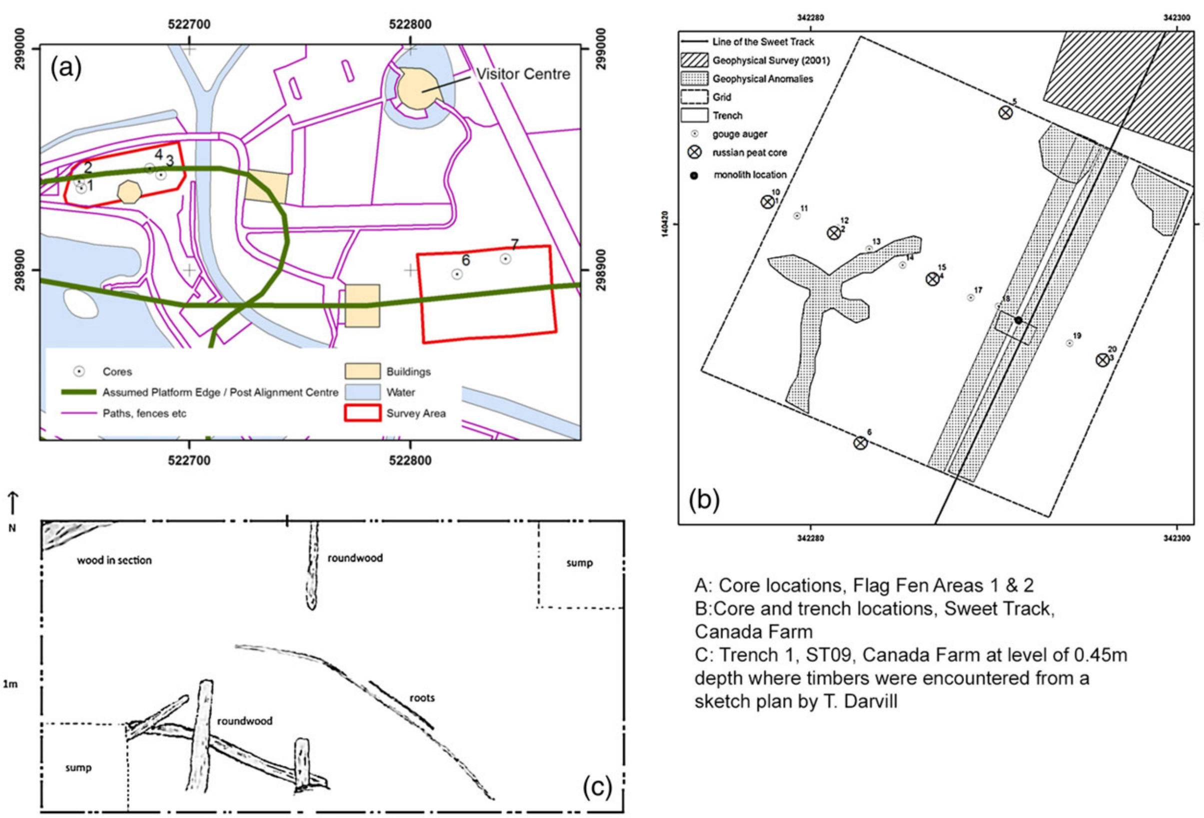

FIGURE 6 Validation work at flag fen (a) and the sweet track (b and c) [Colour figure can be viewed at wileyonlinelibrary.com]

impact on the peat horizon they sit upon. There are other instances of GPR detection of waterlogged timbers (Clarke, Utsi, & Utsi, 1999; Utsi, 2003, 2004, 2007) so this is not a surprising outcome. The resistivity anomaly is co-located with the timbers, but the bog oak was not detected with this technique, reaffirming our suspicion that some other factor is involved. Finally, the magnetic anomaly is somewhat displaced from the trackway as revealed by the other techniques and by the excavation.

To explain the resistivity anomalies, both the linear conductive anomaly and the conductivity gradient, we examined the spatial variation in a number of trace-elements in the cores obtained from the site.

In an exhaustive examination of the physics of electrical resistivity in soils and rocks, Carr (1982) states that the resistance of a body of earth depends on its overall moisture content, the chemistry of said moisture (in particular the concentrations of ions in solution) and the geometrical arrangement of the pore-spaces the water exists within. Earth resistance surveys for archaeology routinely exploit the first of these, and we generally operate under the assumption that the anomalies we identify are caused by differences in absolute moisture content of archaeological features, frequently as a product of their pore-spaces being different (i.e. more or less frequent) than in unaffected soils. However, Carr (1982) went on to further demonstrate that at higher resistances, the overall moisture content becomes so low that changes in resistance brought about by the chemistry of the water become apparent, such as identifying salt water plumes in rocky aquifers. We might also therefore take the inverse to be true; that at points of equal saturation, the effects of chemistry become noticeable because the larger variations produced by total moisture content have evened out to the point that the smaller ones caused by chemical variations become visible.

Carr (1982) gives us four 'operational variables' which explain the conductivity of soil pore water if we conceptualize it as an aqueous solution; 'a) the kinds of ions present in the water, b) their concentration within the water, c) the concentration of conductive colloidal particles, and d) the temperature of the water' (Carr, 1982, 79). At Canada Farm, we can be sure that the temperature and the relative concentration of colloidal particles (formed from both clays and organic matter) were constant, at least in the horizontal plane. Therefore, the ions present and their relative concentrations become the drivers of conductivity changes in the horizontal plane (as we expect that temperature and the concentration of colloids would change with depth and peat-type respectively).

Sodium (Na) is an important element in determining structure/soil moisture, but it is also a key element in the chemical variation of conductivity as well. It forms salts with other minerals and combines with them to form electrolytes which make the pore fluid more conductive (by increasing the concentration of ions, as well as creating conductive colloids). The average sodium concentration (Figure 7) co-varies with the conductivity; it drops as the transect of cores moves west–east (W–E) across the grid, matching the gradient in the geophysical data. It also 'spikes' in the monolith; perhaps creating or influencing the low resistance/high conductivity detected there. Inversely, magnesium (Mg) counts rise, generally speaking from W to E along the main transect, and the depth of their maximum expression comes closer to the surface. This change in the Mg:Na ratio discourages flocculation in clays and organic particles, contributing to higher resistances. The other elements examined included a number of metals, because of their potential to form mineral salts. They were generally found in very low concentrations, or, in the case of aluminium (Al) and iron (Fe) (see Figure 7), to have quite complex patterns with large surface

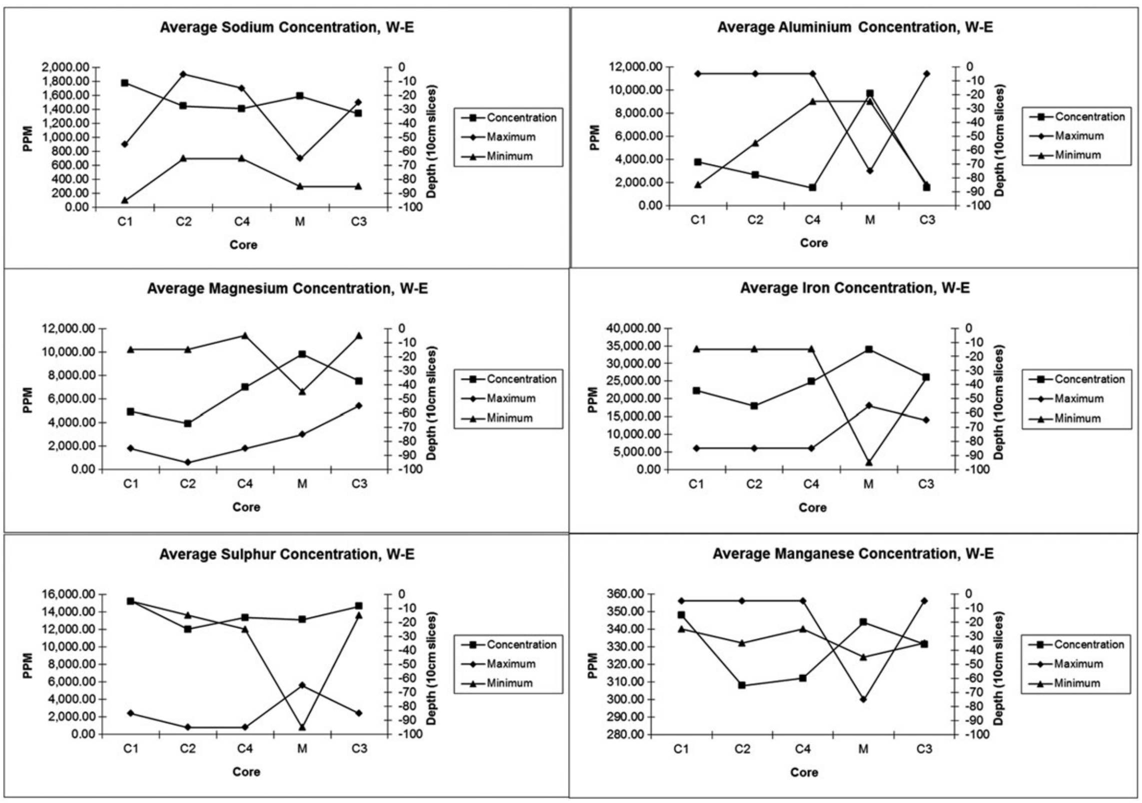

FIGURE 7 Selected average elemental concentrations from inductively coupled plasma (ICP) analysis of cores at the sweet track, Canada farm

concentrations. It is harder to directly relate these elements to conductivity changes, but there are distinct variations in the monolith samples, in contrast to the general distribution patterns in the other cores.

The linear negative magnetic anomaly also requires explanation. Soil magnetism is also affected by both chemical composition and physical factors. Ultimately, the magnetic response is controlled by the mineral present and number of magnetically susceptible particles. This is a function of both the original chemistry of the soil, and the processes it has been subjected to, including the addition of material such as ash, waste products, pottery and food waste, as well as *in situ* heating or burning, and oxidizing and reducing cycles not related to heat. This is further affected by the compaction of the soil; how many of those magnetized or magnetizable particles are packed into a given spatial unit of the soil that is being surveyed (Clarke, 1999; Dalan & Banerjee, 1998; Dearing, 1999; Gaffney & Gater, 2003; Marmet et al., 1999; Thompson & Oldfield, 1986). Given that these soils were saturated, and not considered to be from a settlement, or otherwise anthropogenically influenced, the usual expectations of higher soil magnetism (as measured by magnetic susceptibility) in the topsoil and in the fills of features like pits and ditches did not apply. Instead, we suppose that another source of variation in magnetic minerals produced the gradiometer anomaly: that magnetic minerals were present in either different configurations (impossible for us to measure directly), or in different overall concentrations due to their precipitation out of solution at different stand-still points of the water table [as Boreham et al., 2011 observed at Star Carr].

The exact mechanisms of this were outside the scope of our research; instead, as with the hunt for trace element variations that might explain the conductivity changes, we looked at the overall concentration of iron minerals and the spatial variation in their concentration. As speciation of the iron was impossible, its overall distribution and covariance with sulphur (S) and manganese (Mn) (minerals that commonly form oxides with iron) was examined in the ICP data. All three of these elements are present in a similar pattern, with a slight peak in values at the surface, a drop off, and then an increase in the lower 40–30 cm of the core, and they all vary from this pattern in the monolith. The monolith samples show a slight increase in the average concentration. However at this location, the maximum concentration of iron was higher up in the profile than elsewhere, and the minimum towards the base (see Figure 7).

Without being able to speciate the iron, explanations for this effect are hard to reach, but two things should be considered. Firstly, the anomaly noted in the gradiometer survey was displaced by 1 to 2 m west compared to the other linear anomalies observed. This places the gradiometer anomaly somewhere between Core 4 and the monolith so it is possible the dip in iron concentrations shown in Core 4 in contrast to those in the region of the monolith are producing the anomaly. Secondly, in the magnetic susceptibility tests (see Figure 8), the cores all proved relatively similar, with a pattern of very low values (from just below zero up to about 5SI × 10^{-8}), which tended to fall over depth. The values for samples from the monolith showed much lower values, between 2 and −3SI × 10^{-8}, and very little change with depth, despite the increased iron concentrations, suggesting that some or all of the iron in the monolith was in less magnetic forms.

These very low magnetic susceptibility values were expected, given the waterlogging and the lack of any settlement activity in the vicinity. The differences in the response of the monolith samples, along with the apparently increased and altered distribution of iron and related elements were anticipated from the geophysical surveys, but future research is needed to examine exactly what the causal processes are.

3.2 | Flag fen

At Flag Fen, we conducted a limited coring programme designed to answer two very specific questions. First of all, to locate the cause of the high resistance anomaly in Area 1, thought to be an offshoot of the Roman causeway, and second to locate the depth at which waterlogged soils could be encountered in Area 2, to understand better the 'failure' to detect the timbers of the post alignment in this area. Coring locations (see Figure 6(A)) were selected that should not affect the waterlogged wood; we were not aiming for any wet archaeology. Several cores in Area 1 confirmed the presence of a very hard layer of compacted sand and gravel, almost immediately below the surface identical to the road/causeway construction as visible in the exposed section through this feature on the site. Cores in Area 2 confirmed

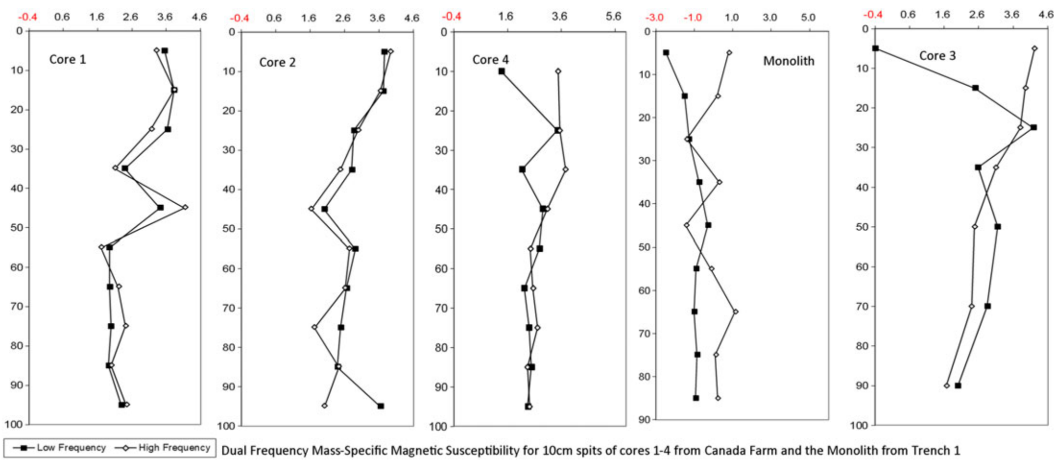

FIGURE 8 Dual frequency mass-specific magnetic susceptibility readings for 10 cm spits of cores 1–4 from the sweet track, Canada farm and the monolith from trench 1 (SI × 10^{-8} kg) [Colour figure can be viewed at wileyonlinelibrary.com]

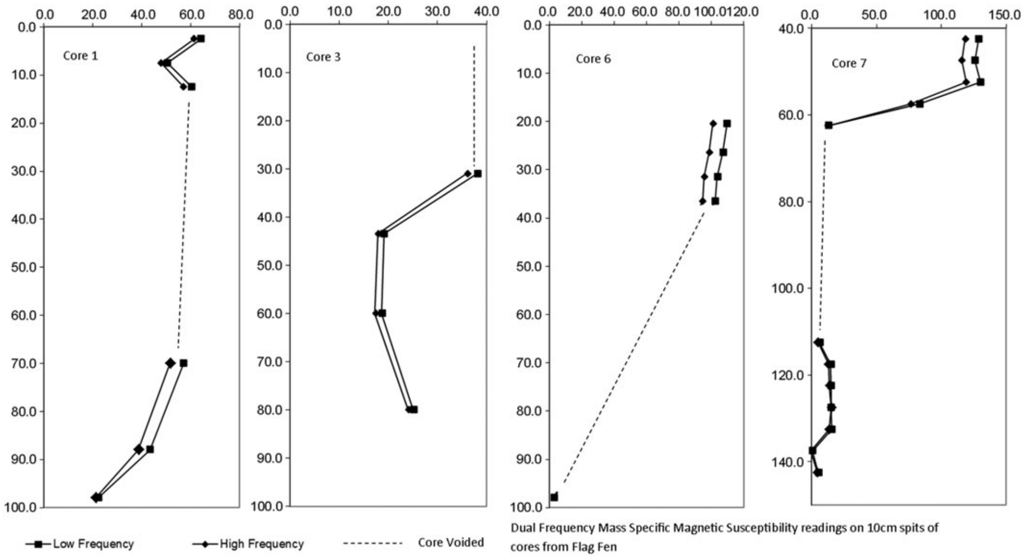

FIGURE 9 Dual frequency mass-specific magnetic susceptibility readings from areas 1 and 2 at flag fen (10 cm spits of material recovered from cores) (SI × 10^{-8} kg)

the complex layering, extreme surface dryness and the presence of a wet layer within 1 m of the surface at this part of the site. The wet layers that were identified were very black, and so presumably strongly oxidized. This is worrying, and hints that a similar round of seasonal shifts in the water table might be causing similar problems as those at Star Carr (Boreham et al., 2011). Magnetic susceptibility tests on the Area 2 cores (see Figure 9) show high values at 45 to 60 cm deep that likely correspond to the post-fen agricultural landscapes visible in the GPR and explains their visibility in the gradiometer data.

4 | DISCUSSION

Despite the low expectations of success on lowland peatland sites, conventional geophysical survey techniques did detect archaeological features, with varying degrees of clarity. In Somerset, we were able to successfully identify an anomaly in the expected location of the Sweet Track in the GPR data, but at the limits of what might be considered 'reasonable' to expect someone to recognize if they were not already aware of its existence. This radar detection is likely a result of different rations of organic matter, minerals and water, combined with the particular structures of wood versus the different types of peat: abrupt boundaries between different Relative Dielectric Permittivity (RDP) values (even if the values are not too far apart) will cause high amplitude reflections. It remains unclear if we were able to directly detect the timbers of the trackway (the wood exposed in the excavation was scattered and small in size), or if the linear group of anomalies more represents general disturbance or differences in the peat at the location of the track: we know that it was put into place during a brief stable period in the peat accumulation and thus lies on an internal horizon within the peat.

The apparent detection of the trackway by resistivity and gradiometry seems likely to be an indirect, or proxy detection. The chemical analysis suggests this was caused by changes in the hydraulic gradient due to the presence of the trackway, resulting in some compounds precipitating out of solution or changing in concentration. The role of peat chemistry, and soil chemistry/geophysical interactions should be a focus for future research efforts.

At Flag Fen, in Cambridgeshire, although we were not able to identify any of the timbers on the site, we provided new insights into the post-fen landscape with the identification of an offshoot of the Roman causeway, and cultivation patterns of uncertain date, not identified in previous studies (e.g. French, 2003). We were also able to identify the driest areas of the site to the responsible archaeologist and make suggestions for future vegetation management.

Picking up the theme of landscape archaeology as a continuum of data (Campana, 2011) rather than a series of 'sites', thus exposing their connective elements and contexts, as elements of the discipline reach for ever larger surveys in even greater detail, we must keep pace in being able to start filling the dark parts of the map; those that are too wet, too dry, too low in contrast. This is likely to require further work on the extreme ends of the detection spectrum: as this article shows in very wet or very dry environments, geochemistry appears to become a driver of observable differences. In surveys covering large landscapes, we will need models of the potential geochemical effects on geophysical properties.

When the results of both sites are taken into account along with the observations from the Vale of Pickering (Boreham et al., 2011) about the effects of fluctuating water tables and acidification, we suggest that geophysical surveys could be developed into effective monitoring tools for waterlogged sites, as well as in their detection and delineation. Near-surface geophysics already has an established role in detecting contamination in ground water, and we could look to the environmental geophysics research community for other useful lines of research to pursue.

5 | CONCLUSION

Though this research was necessarily site-specific, the conclusions and results are more broadly applicable to peatland environments in general, especially comparable ones elsewhere in the UK and northern Europe; the case study sites were selected as well understood representative examples and they have ready parallels in terms of both archaeology and environmental setting. Our research confirms the 2008 observation by English Heritage that GPR might be a useful tool for investigating lowland peatland sites, but we also argue that electrical and magnetic methods should not be discounted as useful secondary surveys to help interpret the GPR data: peatland geophysics is certainly not a lost cause. We further conclude that in saturated soil environments, the chemistry of the substrate and the water within it becomes the driving factor in geophysical characteristics. Further work is needed to understand the mechanisms by which this occurs, and the site formation processes that create spatial differences in geochemistry over short scales.

ACKNOWLEDGEMENTS

The PhD research was funded by Bournemouth University. Access to the sites was facilitated by the Fenland Archaeological Trust (Flag Fen), and Natural England (the Sweet Track). Specific thanks are due to Richard Brunning and Mike Allen for their assistance with the Sweet Track excavations and laboratory work, respectively. The text has been substantially improved by the editors and the reviewers.

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How to cite this article: Armstrong K, Cheetham P, Darvill T. Tales from the outer limits: Archaeological geophysical prospection in lowland peat environments in the British Isles. *Archaeological Prospection*. 2018;1–11. https://doi.org/10.1002/arp.1725