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PII: S0305-4403(15)00150-8

DOI: 10.1016/j.jas.2015.04.010

Reference: YJASC 4413

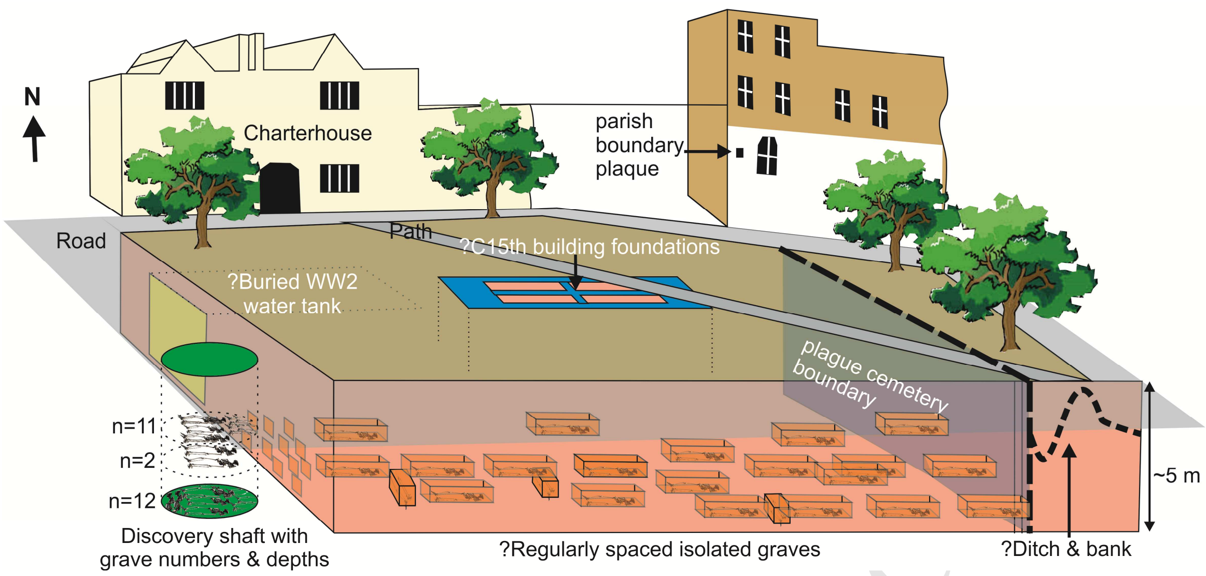
To appear in: *Journal of Archaeological Science*

Received Date: 3 September 2014

Revised Date: 22 April 2015

Accepted Date: 23 April 2015

Please cite this article as: Dick, H.C., Pringle, J.K., Sloane, B., Carver, J., Haffenden, A., Porter, S., Roberts, D., Cassidy, N.J., Detection and characterisation of Black Death burials by multi-proxy geophysical methods, *Journal of Archaeological Science* (2015), doi: 10.1016/j.jas.2015.04.010.


N
Charterhouse
parish
boundary
plaque
Road
Path
?C15th building foundations
?Buried WW2
water tank
plague cemetery
boundary
n=11
n=2
n=12
Discovery shaft with
grave numbers & depths
?Regularly spaced isolated graves
?Ditch & bank
~5 m

Detection and characterisation of Black Death burials by multi-proxy geophysical methods

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Keywords: burials; plague; Black Death; London; geophysics

Abstract

The Crossrail underground network extension discovered 25 well preserved skeletons shallowly buried in Central London in 2013. Subsequent carbon dating and aDNA analysis confirmed the archaeological age and presence of the *Yersinia pestis* "Black Death" plague epidemic strain. Here we present the non-invasive multi-proxy geophysical survey of the adjacent Charterhouse Square, rapidly undertaken to detect any further burials and characterise the site. Historical records suggested the area was a burial ground for Black Death plague victims, before subsequent cemetery and urban land use. Following initial trial surveys, surveys imaged ~200 isolated and similar-sized burials in the south-west of the site. There were also two contrasting burial orientations present at various depths which suggested a series of controlled phased burials. A well-defined eastern burial boundary, taking the form of a ditch and bank, was also discovered. Geophysical surveys also identified a subsequent complex site history with multiple-aged features. This study revises knowledge of Black Death aged-burials and provides important implications for successful geophysical burial detection with significant time- and space-limited site constraints.

1. Introduction

In 2013 Europe's biggest construction project, the Crossrail underground network extension, discovered 25 well preserved skeletons, shallowly buried in close proximity to each other, in Charterhouse Square in Central London. Historical records suggested that the site was an emergency burial ground for Black Death victims during the 1348-1349 AD plague epidemic (Porter, 2009; Sloane, 2011). A non-invasive archaeological geophysical survey of Charterhouse Square with a limited time scale was commissioned because of active construction deadlines.

There are generally accepted to be three plague pandemics in recorded human history, Justinian's Plague (541-542 AD) that was mostly contained within Mediterranean countries, the much wider European so-called Black Death plague (1345-1750 AD) and the 19th Century Chinese plague epidemic which spread globally in 1894 AD (Haensch et al., 2010). The Black Death was the first widespread outbreak of medieval plague in Europe, with recent historical research estimating that it reduced London's population by 30% - 50 % between 1347-1351 AD (Sloane, 2011). Contemporary accounts detail the sheer numbers of dead prevented Christian burials from being undertaken "*so great a multitude eventually died that all the cemeteries of the aforesaid city were insufficient for the burial of the dead. For this reason, many were compelled to bury their dead in places unseemly, not hallowed or blessed; some, it was said, cast the corpses into the river*" (Sloane, 2011).

Recent scientific advancements in dating skeletal remains have allowed research into age of mortality in London during this period (DeWitte, 2010; DeWitte & Hughes-Morey, 2012), subsequent population health improvements (DeWitte, 2014) and confirmation of plague strains to be rapidly identified, usually in the pulp of teeth (Kacki et al., 2004; Drancourt et al., 2004; Bianucci et al., 2009; Haensch et al., 2010). Research has also cast doubt on the traditionally-held premise that rats (*Rattus rattus/norvegicus*) formed the intermediate host carrier in North European countries, with pneumonic (human to human via air droplets) rather than bubonic plague now proposed to be the main dispersal method (Hufthammer & Walloe, 2013).

Current search methods to detect both archaeological and modern human burials are highly varied and have been reviewed (Hunter & Cox, 2005; Pringle et al., 2012a), with best practice suggesting a phased approach, moving from large-scale remote sensing methods (Kalacska, 2009), through to initial ground reconnaissance and control studies before full searches are initiated (Harrison and Donnelly, 2009, Larsen et al., 2011). These full searches can involve many and varied methods, depending upon the individual target(s) and site and even seasonal parameters (see Pringle et al., 2012a; Jervis and Pringle, 2014) through to physical excavation (e.g. see Hunter and Cox, 2005).

Near-surface geophysical surveys have been often applied in archaeological site investigations, either to detect and/or characterise a site (e.g. see De Smedt et al., 2014) or to decide where to start intrusive investigations. Archaeological geophysical searches for unmarked burials are many and have had varied success, for example, locating archaeological graves in Jordan (Frohlich and Lancaster, 1986) and Turkey (Arisoy et al., 2007), Kings' Mounds in Sweden (Persson and Olofsson, 2004), Icelandic Viking/Medieval graves (Damiata et al., 2013), North American Indian historic burial grounds (Bigman, 2012), 19th century cemeteries and graveyards in New Zealand (Nobes, 1999), the USA (Bevan, 1991; Ellwood et al., 1994; Doolittle & Bellantoni, 2010; Dalan et al., 2010; Honerkamp and Crook, 2012; Bigman, 2014), Australia (Buck, 2003), the UK (Hansen et al., 2014), to 19th century Irish Famine victims (Ruffell et al., 2009) and 20th century Svalbard Spanish Flu victims (Davis et al., 2000). The advantages of archaeological surveys are that there is usually little time constraint; however for forensic and time-limited geophysical surveys the need to rapidly characterise a site and identify potential burial position(s) is paramount (e.g. see Nobes, 2000; Pringle and Jervis, 2010; Novo et al., 2011).

Due to the limited survey time and site constraints, a multi-proxy geophysical rapid assessment approach had to be used in this study. Study aims were : ***firstly*** to determine if non-invasive geophysical methods could both detect and characterise the historic burial ground; ***secondly*** to detect any further unmarked burials within the survey area and if there were any particular concentrations and orientations; ***thirdly*** to determine the optimum geophysical technique(s) for such an archaeological time-limited scenario and finally; **fourthly** to compare results to other published studies.

2. Material and methods

2.1 Study site

The study site was at Charterhouse Square near St. Bartholomew's Hospital in Central London, UK, situated ~1 km north of the Thames river and ~15 m above sea level (**Fig. 1**). Charterhouse Square is a 4 acre urban grassed park containing isolated mature deciduous trees, surrounded by roads and buildings with Charterhouse hospital itself to the north-west (**Fig. 2**). Available British Geological Survey boreholes detail an organic-rich silty topsoil succeeded by unconsolidated fluvial sands, gravels and alluvium from previous courses of the River Thames that overlie Eocene London Clay and Cretaceous Chalk bedrock types at ~30 m and ~50 m below ground level (bgl) respectively.

Historical records showed a 13 acre area north of the city walls (**Fig. 1**) was leased by Sir Walter de Mauny in 1349 AD from St. Bartholomew's priory as a burial ground for The Black Death plague victims (Hope, 1925). In 1371 AD de Mauny also sponsored a Carthusian priory and enlarged the site by 4 Acres to the east, the boundary between these areas being a parish boundary that still remains today (Porter, 2009), with a chapel built in 1481 AD and the priory's meat kitchen (Temple, 2010). The priory was dissolved in 1538 AD with the 1348 AD chapel demolished in 1545 AD and the chapel erected in 1481 AD pulled down in 1615 AD; the meat kitchen was probably demolished c.1545 AD (Barber and Thomas, 2002). The buildings of the former priory was rebuilt as a mansion, which was adapted in 1614 AD as an almshouse and school, and after the priory's dissolution the periphery of its outer precinct was built upon, enclosing the modern Charterhouse Square. The construction of the London Metropolitan Railway and a new street built in the 1860s - 1870s AD encroached upon the southern area of the site (Porter, 2009). In 1939 AD as part of World War Two air-raid precautions, six underground emergency water tanks were installed in the square. Lastly an exploratory excavation was undertaken in 1997-8 AD with an isolated skeleton discovered in the north-east of the site (MoLAS, 1998).

Figure 1:

Figure 2:

2.2. Archaeological excavations

As part of the underground network extension, a 4.5 m diameter vertical shaft was dug on the road to the south-west of the Square (**Fig. 2**). At 2.3 m bgl below compacted clay soil, eight isolated earth-cut graves containing eleven relatively well preserved predominantly human remains were encountered aligned northeast-southwest (**Fig. 3a**). These did not show any signs of trauma although further disarticulated human remains were also recovered from two of the grave fills. At 2.5 m bgl two isolated earth-cut graves containing two relatively well preserved incomplete human remains were also encountered, again aligned northeast-southwest. At 2.7 m bgl nine isolated earth-cut graves and one double-grave containing eleven well preserved predominantly adult human remains were encountered, nine aligned northeast-southwest and two aligned north-south (**Fig. 3b**). The deepest burials had two graves with multiple burials, one with remains on top of the first and the other having them side by side (**Fig. 3b**). Recovered pottery shards from the 2.3m bgl burials estimated a burial date of 1270-1350 AD.

Subsequent radio-carbon dating of the 2.5 m and 2.7 m bgl burials gave date ranges of 1275 AD -1405 AD ±20BP, with the 2.3 m bgl burials having a date range of 1430 AD – 1485 AD ±21BP (see MoLAS, 2013). Rapid aDNA analysis (see Kacki et al., 2004) of the recovered human remains confirmed the presence of the *Yersinia pestis* Black Death plague epidemic strain in all three burial phases (**Fig. 3** and MoLAS, 2013).

Figure 3:

2.3 Near-Surface geophysical investigations

After initial trial surveys showed detectable anomalies following best practice (see Milsom and Eriksen, 2011), a two day time-limited survey was then undertaken. 2D profile positions (**Fig. 2a**) were all surveyed using a Leica™ 1200 total station theodolite and reflector prism with an 0.005 m average position accuracy before being integrated with the digital sitemap in ArcGIS™ ArcMap v.10 software.

A bulk ground conductivity survey was undertaken over the whole square using a Geonics™ EM-31-Mark2 conductivity meter (**Suppl. Mat.**), not to identify individual grave positions but in order to rapidly characterise the site and to determine the spatial limits of the burial area. This instrument images bulk changes in the near-surface, typically down to ~10m bgl in ideal conditions (see Milsom and Eriksen, 2011). It was expected that there should be a measureable EM contrast across the burial area margins, any relict building infrastructure to be clearly imaged as isolated high/low linear anomalies and the highly conductive water tanks to be found if remaining. The instrument was zeroed at the northeast side of the square which was determined to be relatively geophysically homogeneous from the trial surveys. Due to potential cultural interference from above-ground conductive objects, the dataset was collected with the meter in vertical orientation (VMD) mode which did reduce its sensitivity to very near-surface objects (see Milsom and Eriksen, 2011). Both inphase and quadrature data types were collected on 2 m spaced survey lines in a one-way, west-east orientation across the square at ~0.5 m spatial position increments. A Garmin™ GPS also logged sample positions and was used by Trackmaker31™ v.1.21 to check positional locations. Standard post-survey data processing was undertaken in Geoscan™ Geoplot v3.00 software, including data de-spiking to remove isolated anomalous data points and de-trending to remove long wavelength site trends from the data, before the dataset was imported into ARCGIS ArcMAP™ v.10 software and a digital, colour contoured surface was generated using ordinary kriging through the Geostastical Analyst extension.

An electrical resistivity survey was only collected over the south-west area of the site due to time constraints as other studies (see e.g. Hansen et al., 2014; Ellwood et al., 1994) have imaged relative low/high isolated resistivity anomalies associated with historic burials, compared to background values. Whilst 0.5 m probe spacing configurations are commonly used for such investigations (see e.g. Hansen et al., 2014; Pringle and Jervis, 2010), a 1 m probe separation was used here to penetrate to the ~3 m depths of the discovered graves (**Fig. 3**). Remote probes were set at least 10 m from sample positions following best practice guidelines (see Milsom and Eriksen, 2011). Geoscan™ RM15-D bulk ground electrical resistivity equipment (**Suppl. Mat.**), with a stated measurement accuracy of 0.1 Ω, was used to collect 1 m x 0.1 m spaced data over a limited area of 8 m x 38 m, located adjacent to the discovered burials (L1-8 in **Fig.2** for location). After data download, standard post-survey data processing were undertaken in Geoscan™ Geoplot v.3.00 software, including; (i) conversion of measured resistance (Ω) values to apparent resistivity (Ω.m) to account for probe configuration; (ii) data de-spiking to remove isolated anomalous data points and; (iii) dataset de-trending to remove long wavelength site trends from the data (see Milsom and Eriksen, 2011). The dataset was then imported into ARCGIS ArcMAP™ v.10 software and a digital, colour contoured surface was generated using ordinary kriging through the Geostastical Analyst extension.

A Ground Penetrating Radar (GPR) dataset was also collected over the south-west area of the site, as other authors have found this method effective to detect unmarked archaeological burials as discussed in the introduction. Due to time constraints, widely-spaced and orientated 2D profiles were also collected in the rest of the square to detect if further graves were present, and to determine the spatial burial area extent and its margins (**Fig. 2** for location). After the trial surveys determined the optimum radar frequency, GPR PulseEKKO™ 1000 equipment was utilised with 225 MHz frequency antennae and a 32 v transmitter antennae (**Suppl. Mat.**) to collect the data with 0.1 m trace spacings , 90 ns time window and constant 32 repeat stacks. A grid of 1-m spaced 2D profiles were acquired adjacent to the discovered archaeological graves (L1-21), three (L22-24) acquired on the road to the north of the square, two (L25,29) orientated at right angles to the parish boundary, one (L26) outside the parish boundary and a final profile (L28) mid-way across the square. Standard data processing steps were undertaken in REFLEX-Win™ v.3.0 processing software, these included; (1) subtracting the mean from traces; (ii) picking first arrivals and then (iii) applying static correction and moved trace start times to 10 ns; (iv) time-cut to remove blank data and; (v) manual gain 1D filter to boost relative deeper radar trace amplitudes whilst retaining shallow ones.

Two 2D Electrical Resistivity Imaging (ERI) profiles, orientated at right angles to the known parish boundary, were also collected by a CAMPUS™ TIGRE system (**Suppl. Mat.**) to determine if this marked the burial margin (**Fig.2** for location). As with the conductivity data, it would be expected that there would be a sharp contrast in resistive properties across this margin. Both profiles used 32 steel electrodes inserted into the ground along each profile, with ERI1 and ERI2 using 1 m and 0.5 m probe spacing respectively due to site constraints. ImagerPro™ 2000 data acquisition software used a Wenner configuration and 10 'n' levels that should penetrate to ~5 m bgl as shown by other researchers (see e.g. Brown, 2006; Pringle et al., 2012b). Raw ERI datasets were then individually processed with anomalous data points removed and inverted utilizing least-square inversions in Geotomo™ Res2Dinv v.355 software following standard methods (see Milsom and Eriksen, 2011). Half cell spacing was also utilized during the inversion process to remove potential edge effects and reduce any probe contact resistance variations. Finalised models of true resistivity sections were created with a relatively small RMS mis-fit of 2.5 % (ERI1) and 4.1 % (ER2) between the respective calculated models and acquired datasets (see Milsom and Eriksen, 2011).

3. Results

The processed bulk ground EM conductivity dataset, acquired in order to characterise the site and determine the spatial limits of the burial area, showed a relatively highly conductive 15 m^2 rectangular area in the north-west of the square, compared to background values, which will most probably be the location of the WW2 water tank (**Fig. 4**). There was also a relatively high conductive area in the south, but this was probably due to the presence of the above-ground metal fence that bordered the urban square. There was a relative low conductive ~25 m^2 area in the north-east of the square whose origin could not be determined (**Fig. 4**). In contrast, there was also a ~20 m^2 square anomaly with variable relative high/low conductive values in the central area (**Fig. 4**); this was of similar size to a meat kitchen documented to be onsite. Interestingly there was no measureable difference in EM properties across the parish boundary as was expected (**Fig. 4**).

Figure 4:

The processed electrical resistivity survey of the south-west area of the square, adjacent to the discovery shaft, showed a trend from very high resistivity values in the south to very low resistivity values to the north (**Fig. 5**). The north area therefore agrees with the high conductivity values in the EM dataset. However relative isolated anomalies compared to background values, which may be expected from individual graves containing human remains (see Frohlich & Lancaster, 1986; Hansen et al. 2014), were disappointedly not observed in this dataset. This may be due to this survey not penetrating to their likely 2+ m depths below ground level.

Figure 5:

The processed 2D GPR profiles in the western of the square (L1-21 – see **Fig. 2**) consistently imaged isolated, evenly-spaced and similar-sized ½ hyperbolic reflection events produced from buried objects in the southern half of all profiles (**Fig. 6**). These objects were between ~1.5 m to ~3 m bgl that were similar to the discovered historic graves (**Fig. 3**) and have been observed in other mass burials (e.g. Ruffell et al., 2009). Smaller and shallower ½ hyperbolic reflection events were due to tree roots from mature deciduous trees onsite . Consistent, very strong horizontal reflections for ~10 m – 12 m were also present at the northern end (**Fig. 6**), with both a top at ~0.5 m bgl and bottom ~2 m bgl reflector observed (*cf.* **Fig. 6**). This significant-sized object was correlated to the high conductivity/low resistivity anomaly present in both the EM and electrical resistivity datasets respectively and was the water tank. Due to time constraints the profiles were too widely-spaced for meaningful horizontal time slices to be generated.

The other 2D profile (L28) across the park (**Fig. 2** for location) showed multiple isolated ½ hyperbolic reflection events in the southern side, with none present in the north, although there was no strong horizontal reflector present (**Fig. 6**). Three 2D profiles (L22-24) on the north to the north of the square (**Fig. 2** for location) did not image any objects, except beside observed surface manhole covers. The 2D profile (L26) that was located east of the parish boundary did not show any characteristic isolated ½ hyperbolic reflection events (**Fig. 6**).

Figure 6:

Both 2D ERI inverted models showed a clear contrast in resistivity properties across the parish boundary, with relative higher resistivity values to the east of boundary and lower values to the west, in contrast to the EM data (cf. Figs. 4 and 7). However, the GPR showed much better resolution at this location, resolving a potential ditch and bank geometry at the margin (**Fig. 7**). There were significant heterogeneities present in both profiles, as would be expected in such urban environments, variable moisture content may also be a factor here as others have found (Pringle et al., 2012b), especially in parklands (Jones et al., 2009).

Figure 7:

4. Discussion

The first aim of this study was "*to determine if non-invasive geophysical methods could both detect and characterise the historic burial ground*". The geophysical surveys have identified the key characteristics of the site. These confirmed that the eastern boundary was the marked parish boundary, a square anomaly in the centre may be buried foundations of the priory's meat kitchen, shown on mid-fifteenth century plans to have been a two-story building, or, perhaps less likely, a demolished chapel. WW2 buried water tanks remain in the north-west area and lastly, but most importantly, a concentration of ~200 isolated buried objects were present in the south-west of the square. These 200 objects were most probably further, and as yet undiscovered, isolated graves of Black Death plague victims although this will need to be excavated for confirmation. The eastern boundary also had a central ditch and eastern raised bank identified by GPR that that matched historical accounts (Porter, 2009). **Figure 8** and **Table 1** summarise the study findings. These targets were still geophysically detectable in a difficult urban survey environment, the burials after 660+ years, showing that archaeological geophysical surveys can both detect and characterise historic burial sites. Note that any further archaeological targets in the Square's boundaries may not have been geophysically resolved due to local cultural noise.

Figure 8:

Table 1.

The second aim of this study was "*to detect any further unmarked burials and if there were any particular burial concentrations and orientations*". The SW of the square showed multiple, evenly-spaced and shallow buried objects which were most likely to be historic graves (**Fig. 8**). Simple identification of anomalies in GPR 2D profiles gave a conservative estimate of ~200 individual graves; note that there will, most probably, be more due to co-mingled remains as both this study (**Fig. 3**) and others, for example, the Kacki et al. (2011) study of contemporary remains in French cemeteries, have evidenced. Historical records suggest that there may be several thousand individuals buried in this area (see Sloane, 2011), but it was unknown what burial style they may be, and if they had been removed subsequently. The mostly isolated nature of burials was surprising; it was documented that burials during the height of the Black Death plague epidemic were buried in mass pits (Sloane, 2011) and thus this study has revised the knowledge of burials to more of an emergency cemetery style. The discovered burials also had three clearly different burial phases, with clay-rich soil being deposited between each, perhaps in an attempt to prevent the spread of the disease (**Fig. 8**). Some geophysical anomaly orientations were similar to the discovered graves, approximately northeast-southwest, but there were other orientations, north-south orientated burials for example. There do not seem to be remains in the north of the Square and indeed outside the eastern parish boundary.

The third aim of this study was "*to determine the optimum geophysical technique(s) for such an archaeological time-limited scenario*". To successfully detect and characterise historic burials a multi- phased approach using different geophysical techniques should be undertaken following best practise (see Harrison & Donnelly, 2009; Larsen et al., 2011;

Pringle et al., 2012a). In this case, after the desk study of historical records and remote sensing data had identified the burial site, during initial site reconnaissance, as well as soil and bedrock type being determined, trial surveys using available non-invasive geophysical equipment were undertaken. Electro-magnetic, electrical resistivity and GPR methods were all trialled to determine if targets were geophysically detectable, i.e. measureable from background values. EM surveys then rapidly surveyed the site, with bulk ground change areas being identified. These areas were then re-surveyed by higher resolution geophysical methods, particular GPR, and this phased approach is recommended for other studies. Trial surveys also determined optimal geophysical equipment configurations. For example, GPR 225 MHz frequency antennae were judged optimal, mid-range frequency have also been shown by other studies to detect buried archaeological objects buried at least 1 m depth bgl (see Davis et al., 2000; Ruffell et al. 2009; Ruffell & Kulessa 2009; Hansen et al., 2014) which gave confidence in the survey data collected. The electrical resistivity survey equipment configuration was also used with 1 m electrode spacing on mobile probes, a less-used spacing as 0.5 m is conventional (see Pringle et al., 2012b; Hansen et al., 2014) but one deemed to be able penetrate to the desired depth bgl. Whilst the WW2 underground tanks were identified, individual remains were not using this method; this was most probably due to the heterogeneous nature of the site. ERI 2D profiles were judged very useful in this studyto characterise the burial boundaries, but the GPR 2D profiles on the same survey lines had better resolution and allowed the nature of the boundary to also be determined. Combining different geophysical techniques to gain extra information has also been recommended by other authors (e.g. see Milsom & Eriksen, 2011; Pringle et al., 2012b).

The fourth and final aim of this study was "*to compare results to other published studies*". In the literature GPR has been commonly used to detect archaeological graves, for example ancient graves in Jordan (Frohlich & Lancaster, 1986) and Viking/Medieval graves in Iceland (Damiata et al., 2013), and unmarked graveyard and cemetery burials in New Zealand (Nobes, 2000), Australia (Buck, 2003), the US (Doolittle & Bellantoni, 2013), Ireland (Rufell et al., 2009) and the UK (Hansen et al., 2014), and marked burials in Germany (Fiedler et al., 2009b). These studies have all used mid-range GPR antennae which this study has also utilised after trial surveys. There are fewer published studies using electrical resistivity to locate individual remains and indeed characterise mass burial sites, Witten et al. (2001) used electrical resistivity to locate a 1920s race riot burial site in the US and Brown (2006) used ERI 2D profiles to locate 1990s burials in Bosnia. For bulk ground conductivity De Smedt et al. (2014) documented an EM survey to characterise the Stonehenge archaeological site, but there is only Bigman's (2012) study to locate unmarked graves in North American Indian burial grounds and Nobes (2000) New Zealand clandestine grave search. However all of these were in rural environments which was not the case here, albeit De Smedt et al. (2014) documented advanced processing was needed to remove the effect of near-surface metallic clutter from the data. From the data in this study it is suggested to use EM techniques to characterise the site before using ERI 2D profiles to characterise site margins, followed by mid-frequency radar surveys to characterise their content. It was impressive that near-surface geophysical surveys have been so effective in such a busy urban environment.

4. Conclusions

Following the discovery of historic skeletal remains and subsequent radiocarbon dating and aDNA analysis confirmed individuals were victims of the Yersinia pestis Black Death plague epidemic in the 14th and 15th Centuries, a multi-technique near-surface geophysical survey was undertaken in Charterhouse Square in central London. An EM, ERI and GPR survey rapidly characterised the site, finding the eastern boundary of a burial ground with suspected ditch and bank that matched historical records. There were concentrations of ~200 surprisingly isolated burials in the south-west of the site, with two different burial orientations and three different burial depths below ground level. These suggest different phases of burial over different time periods that was confirmed by radiocarbon dating. The square formed part of an emergency cemetery at this time, rather than mass burial pits/trenches that was documented in historical records. Geophysical investigations also characterised the site with subsequent demolished building foundations and WW2 water tanks remaining on site. This study revised existing knowledge of Black Death burials and shows the potential of near-surface geophysical techniques to both detect and characterise historic mass burials in busy and restrictive urban environments.

5. Acknowledgements

This study was financially supported by TrueNorthTV Productions. Sarah Aldridge from University College London and Matteo Giubertoni from Polimi University are acknowledged for field assistance. A 2003 SRIF3 grant supported the purchase of geophysical and survey equipment at Keele University.

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Figures:

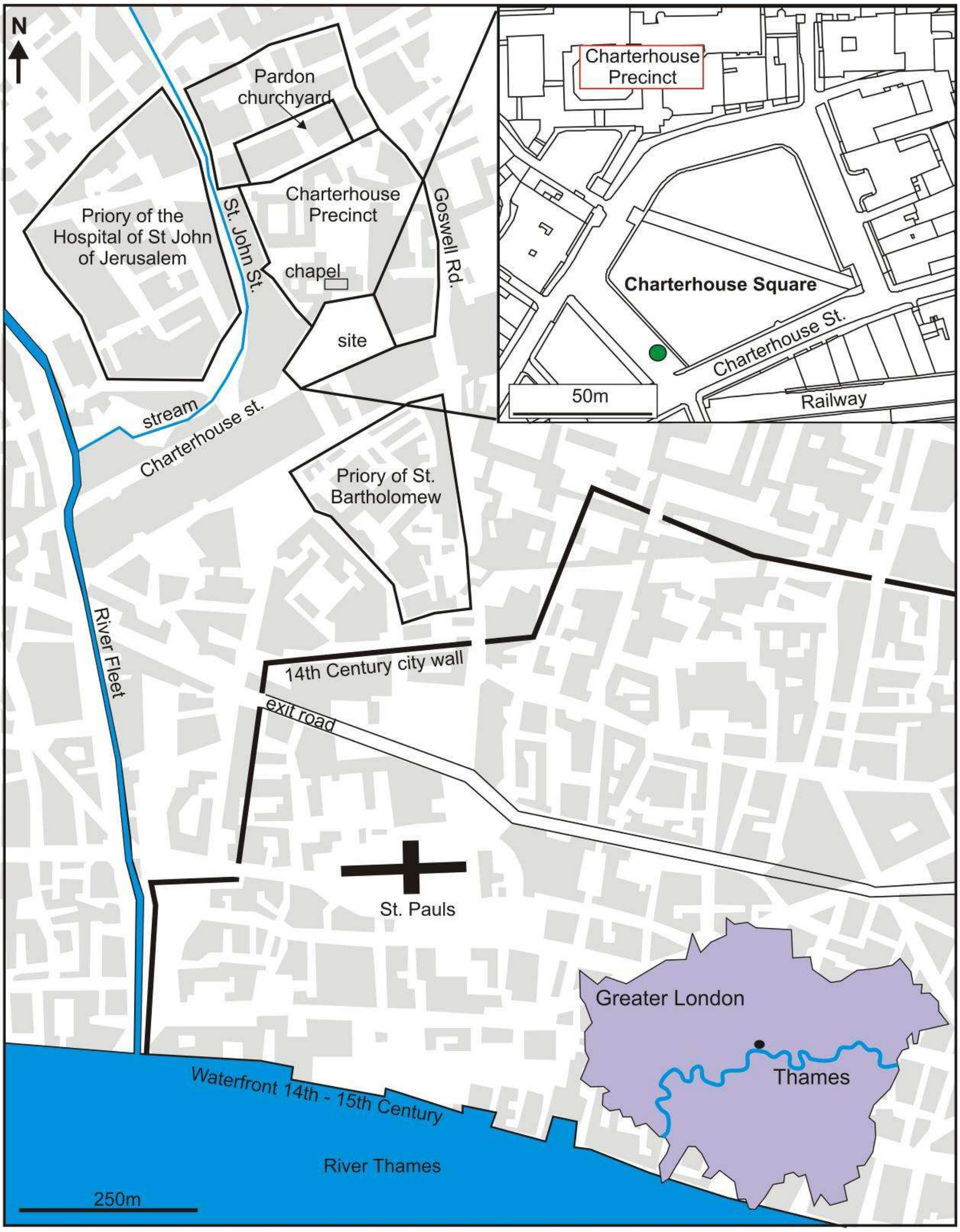
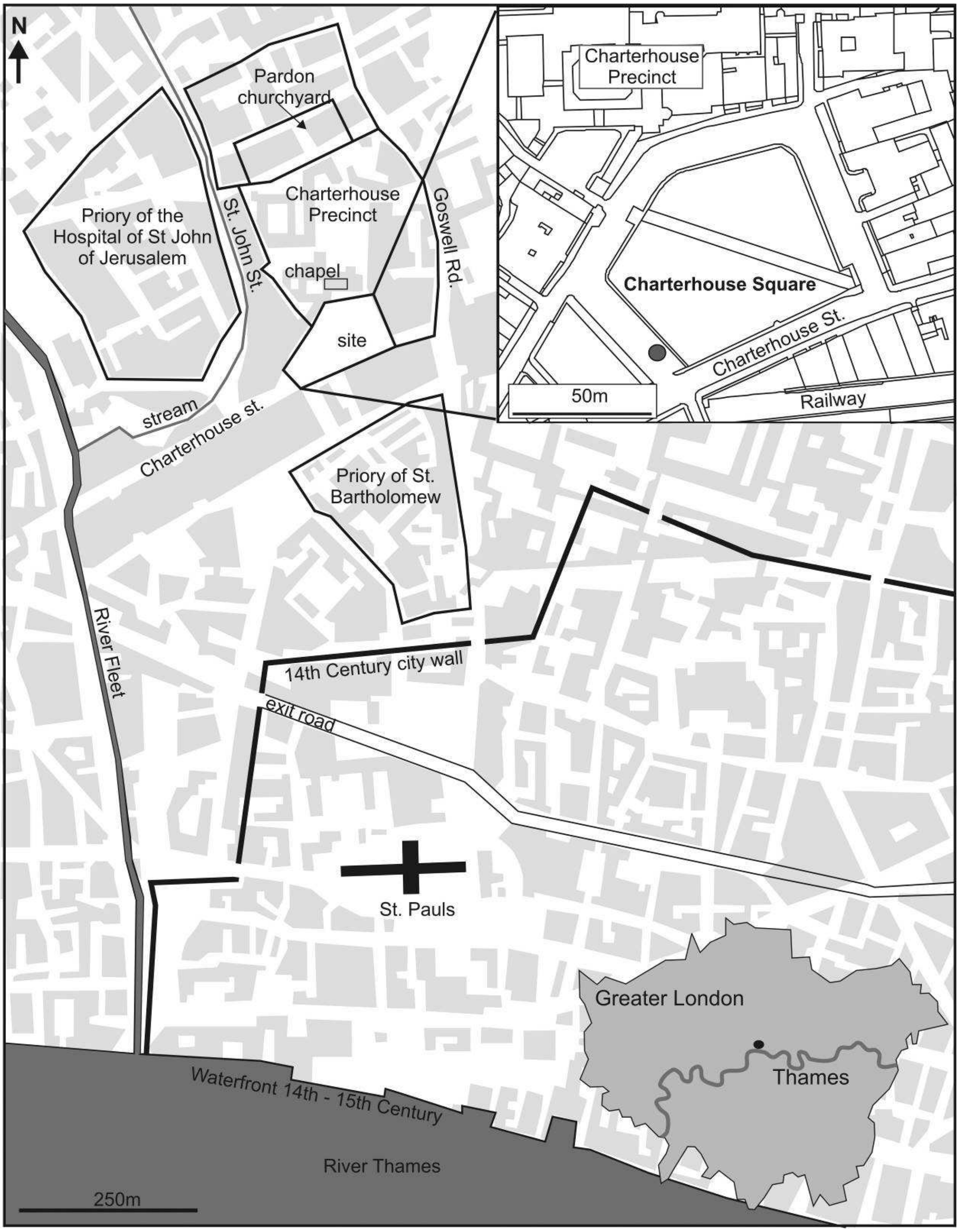


Figure 1: *Map of the general and specific survey area (with location inset) and relevant Medieval features superimposed (after MoLAS, 2013).*



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597 ***Figure 1:*** *Map of the general and specific survey area (with location inset) and relevant*

598 *Medieval features superimposed (after MoLAS, 2013).*

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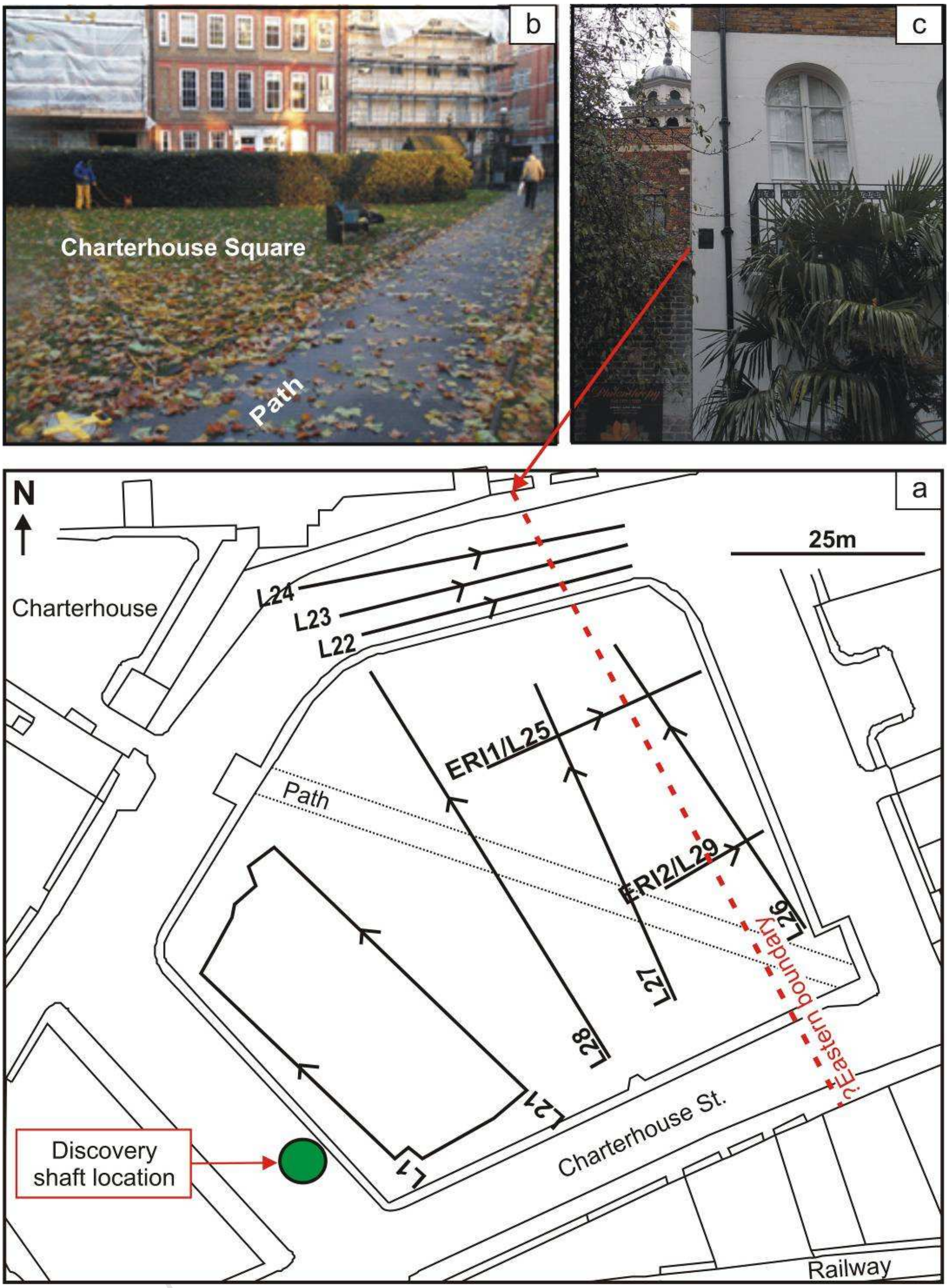

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601 ***Figure 2:*** *a) Mapview of Charterhouse Square showing discovery shaft location (circle),*

602 *named geophysical survey lines and orientations, parish boundary (dotted), b) site*

603 *photograph and c) parish boundary building plaque.*

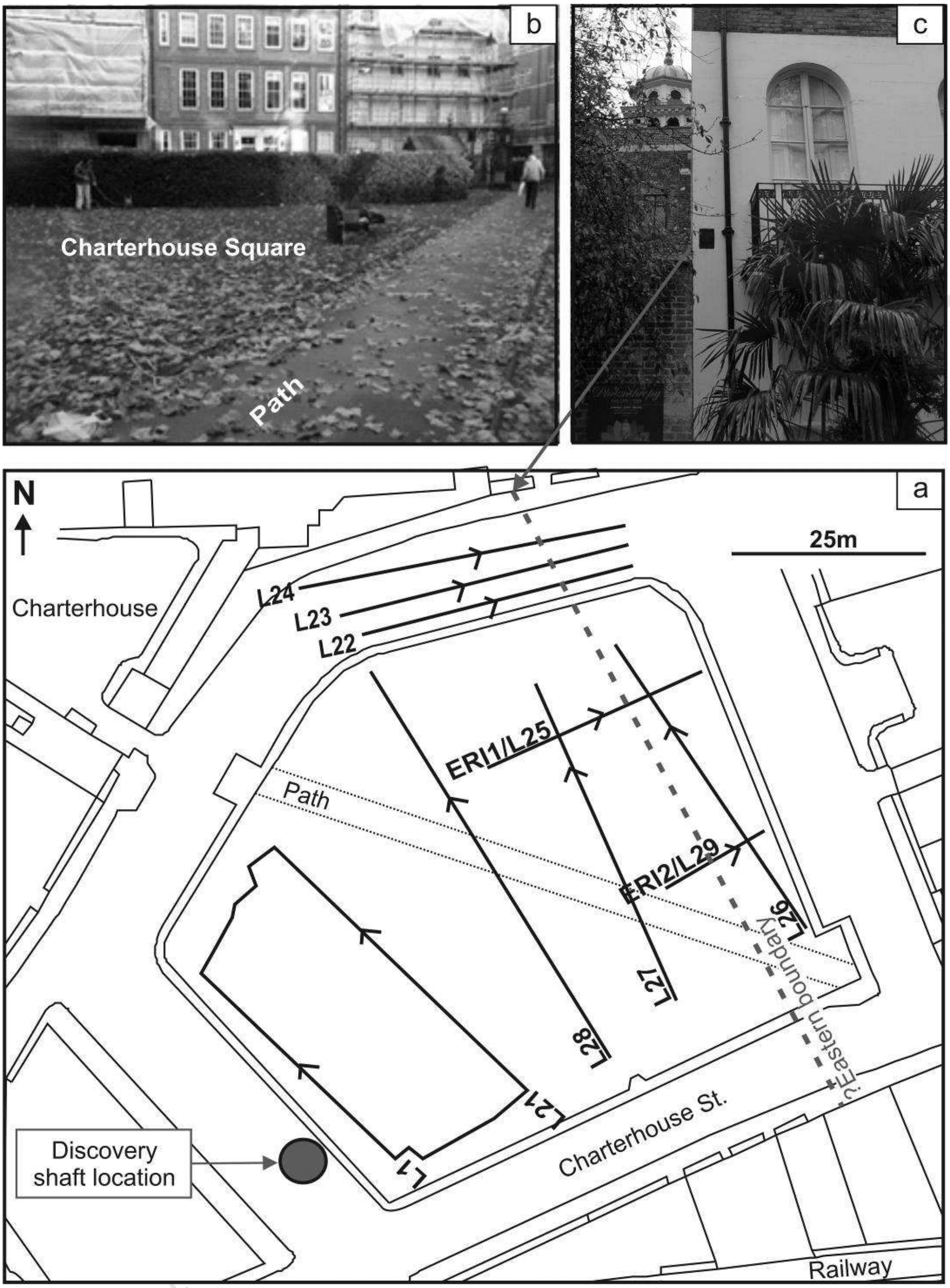


Figure 2: *a) Mapview of Charterhouse Square showing discovery shaft location (circle), named geophysical survey lines and orientations, parish boundary (dotted), b) site photograph and c) parish boundary building plaque.*

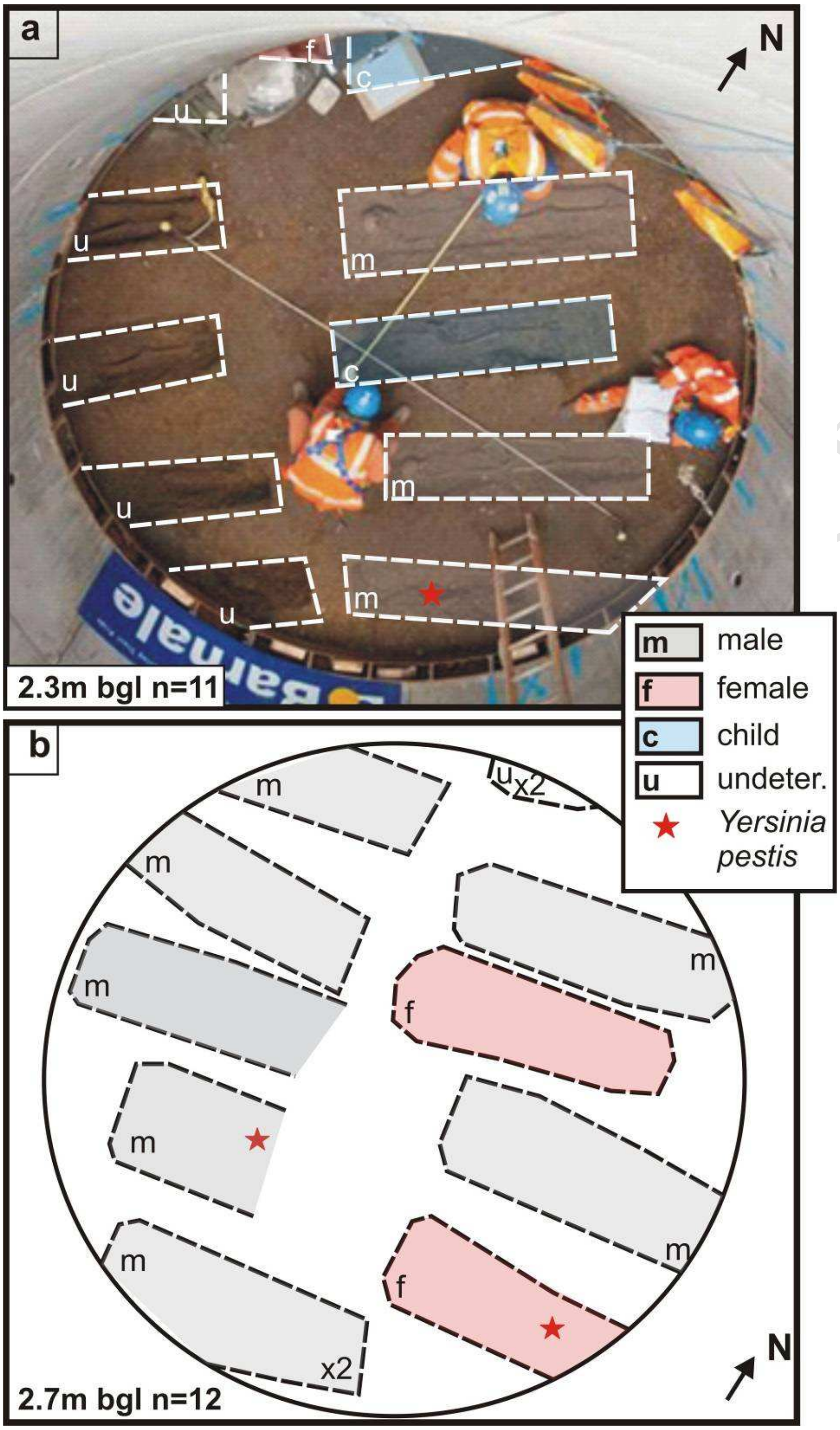
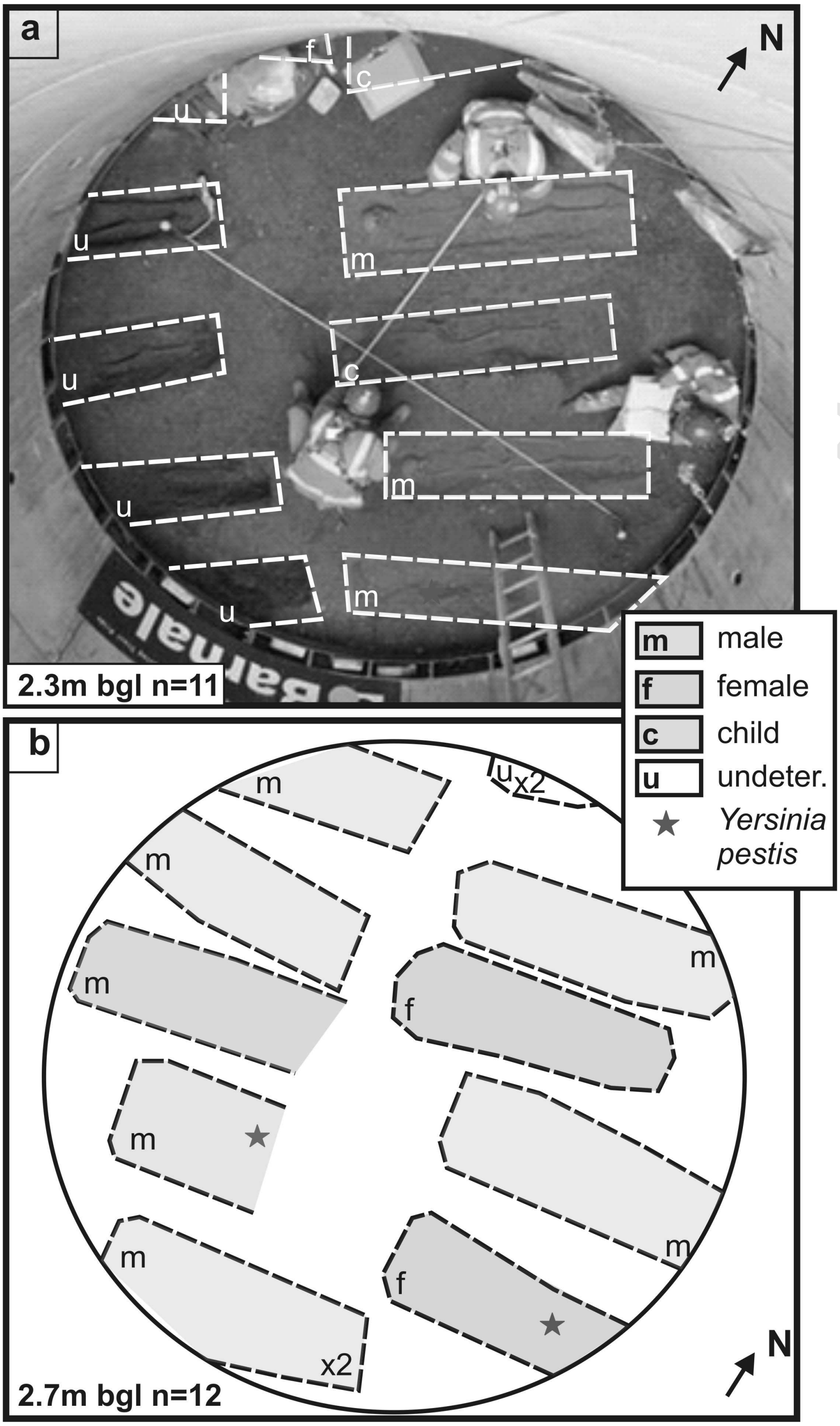


***Figure 3:** Mapview of shaft discovered earth-cut graves with identified burials and confirmed Yersinia pestis (see keys) at (a) 2.3 m and (b) 2.7 m BGL respectively (**Fig. 2** for location). Two graves discovered at 2.5 m BGL not shown. Modified from MoLAS (2013).*



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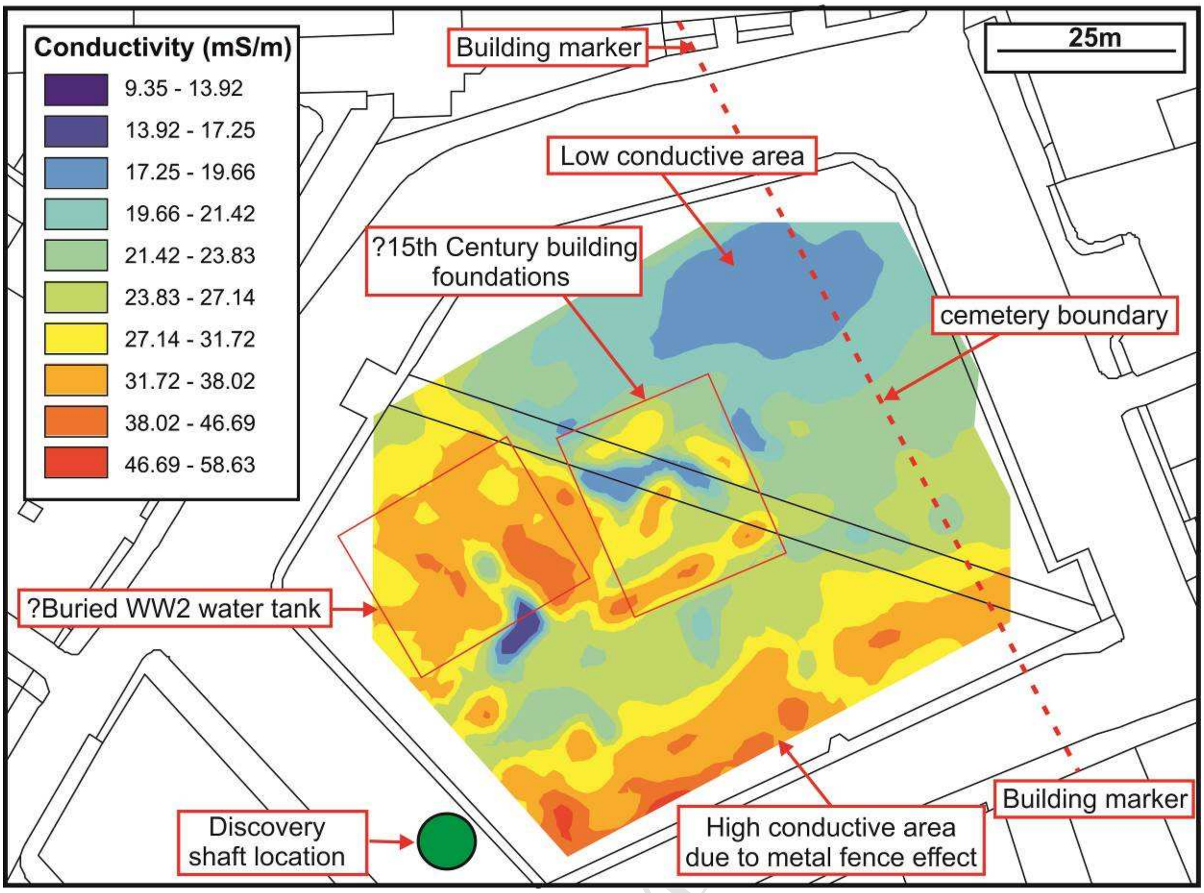
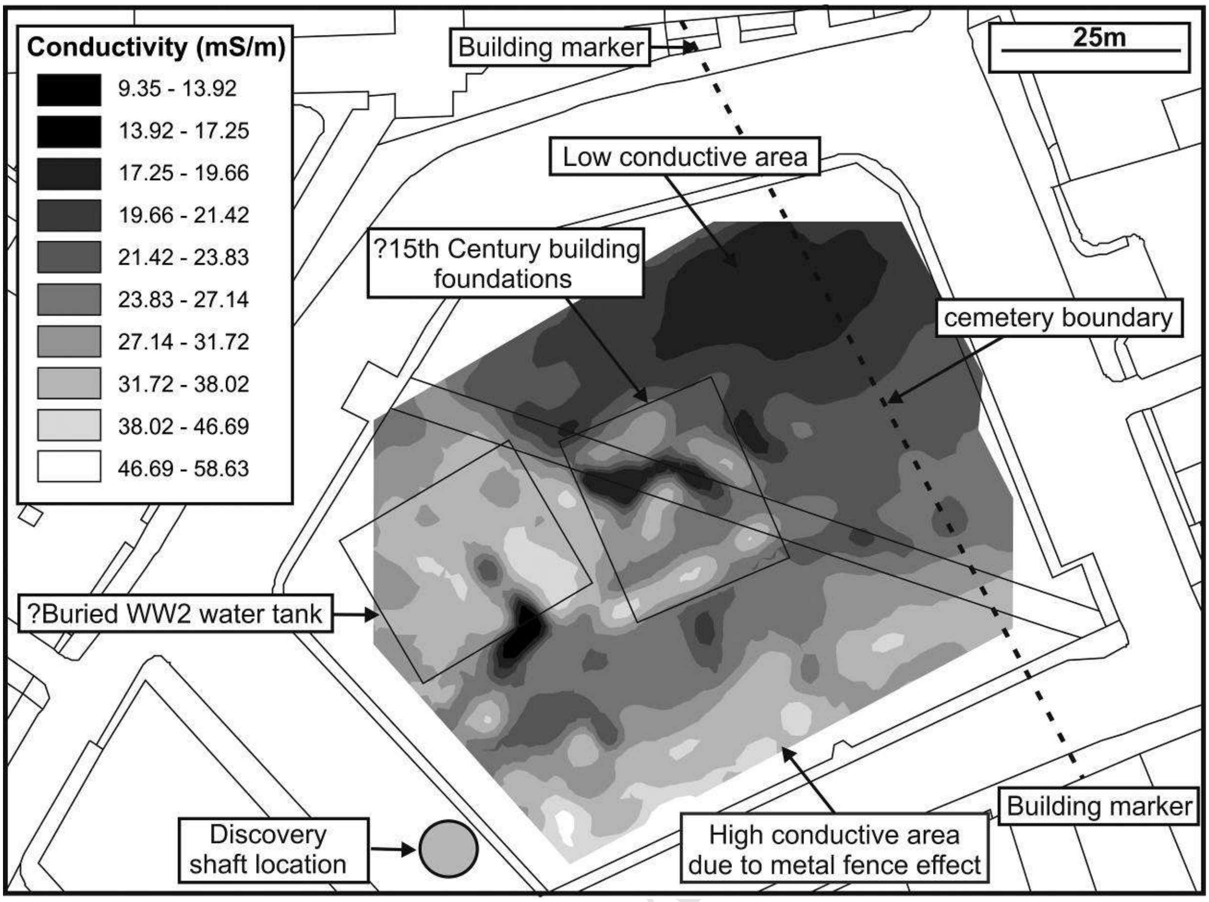


Figure 4: *Processed electro-magnetic (EM) conductivity Quadrature dataset with contoured digital surface (see key) and annotated interpretations.*



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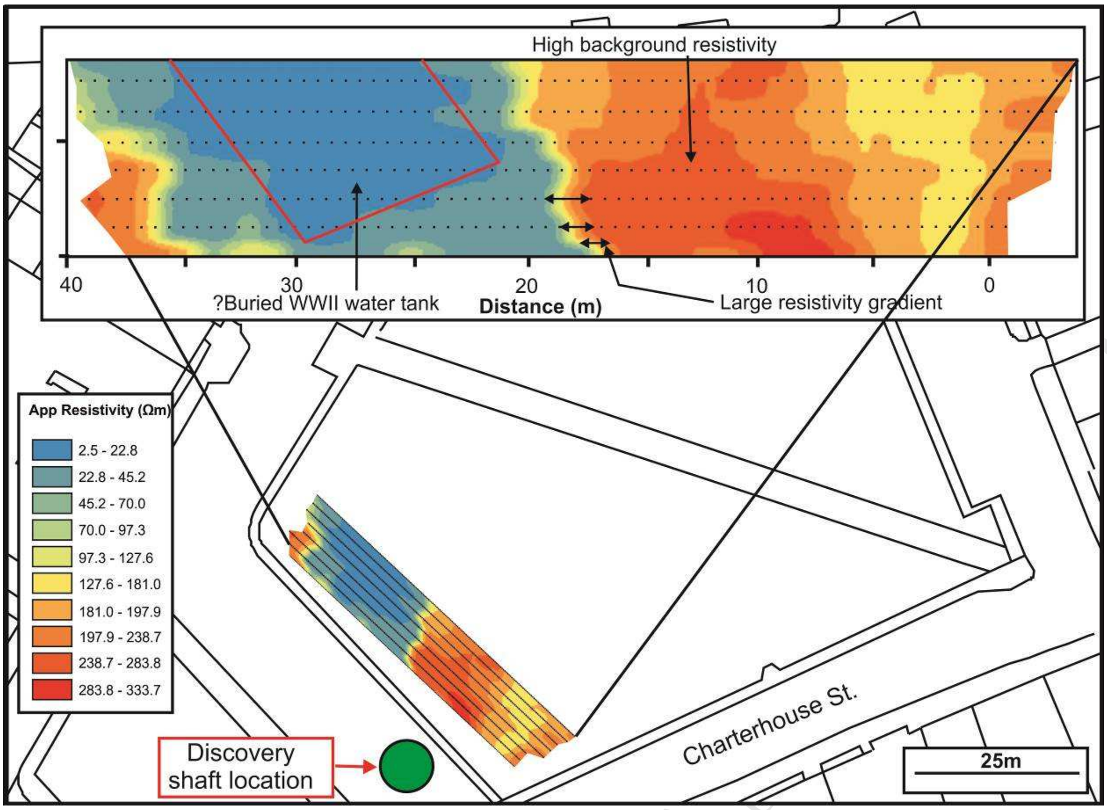

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624 ***Figure 5:*** *Processed electrical resistivity dataset with contoured digital surface (see key) and*

625 *annotated interpretations.*

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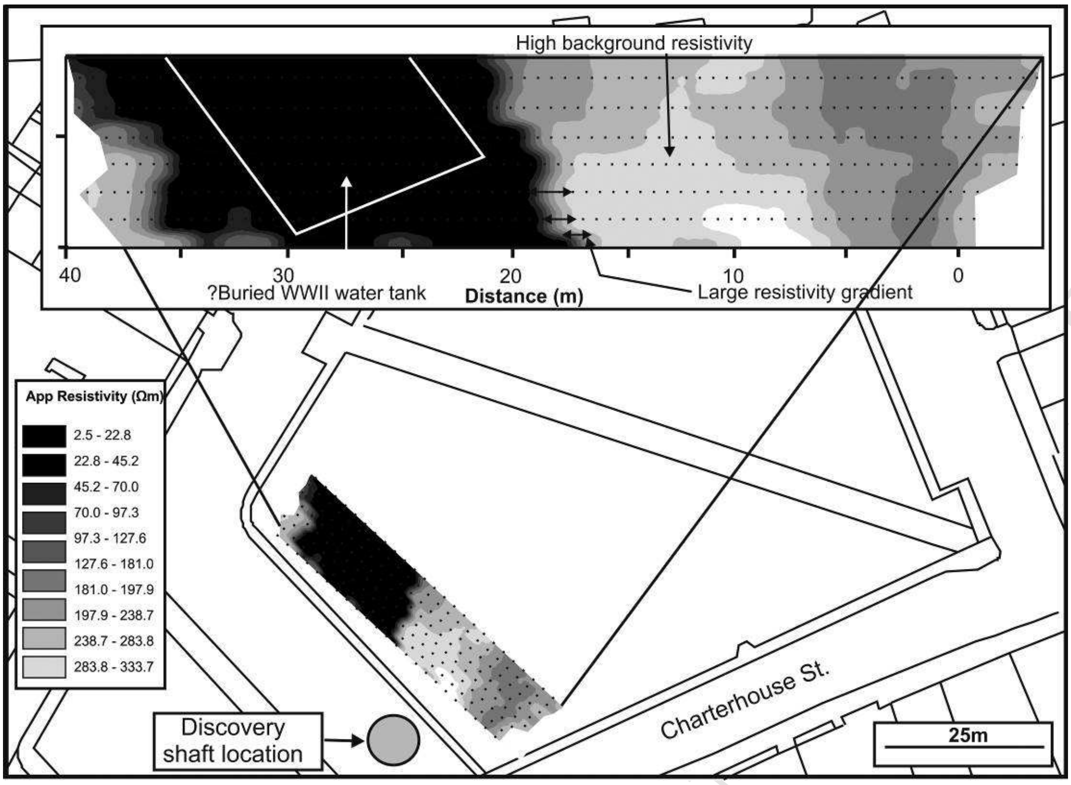

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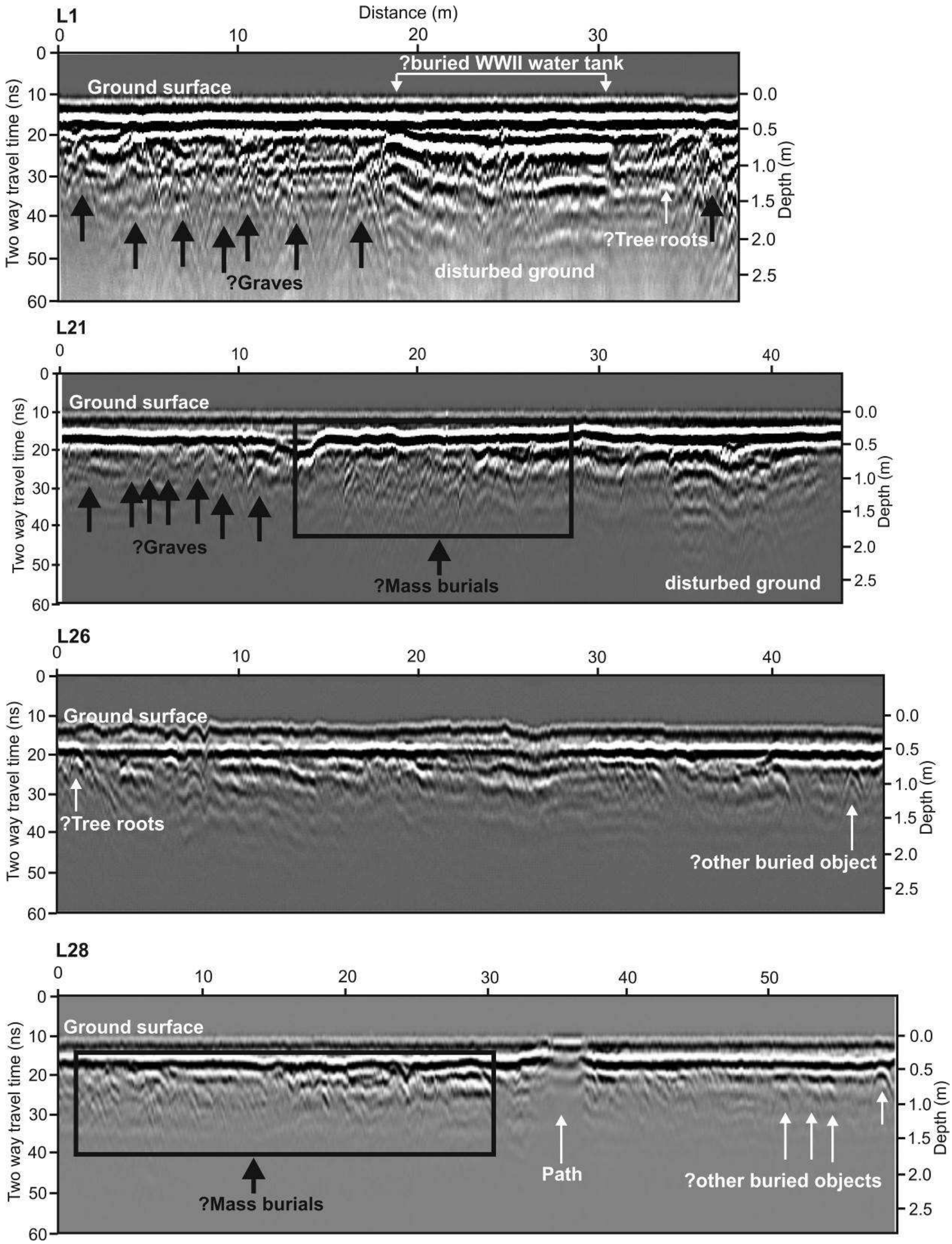


Figure 6: *Selected GPR 2D interpreted profiles all orientated south to north(**Fig. 2** for location). Note L26 is to the east of the parish boundary.*

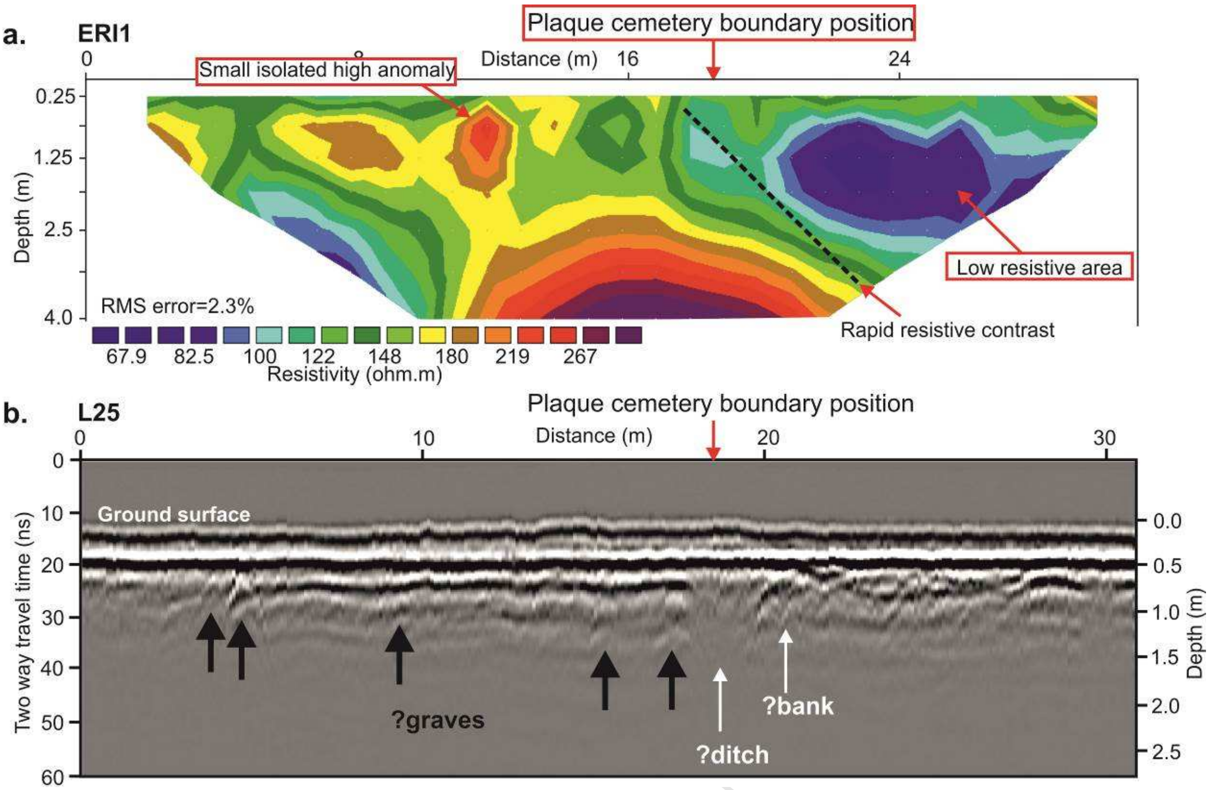
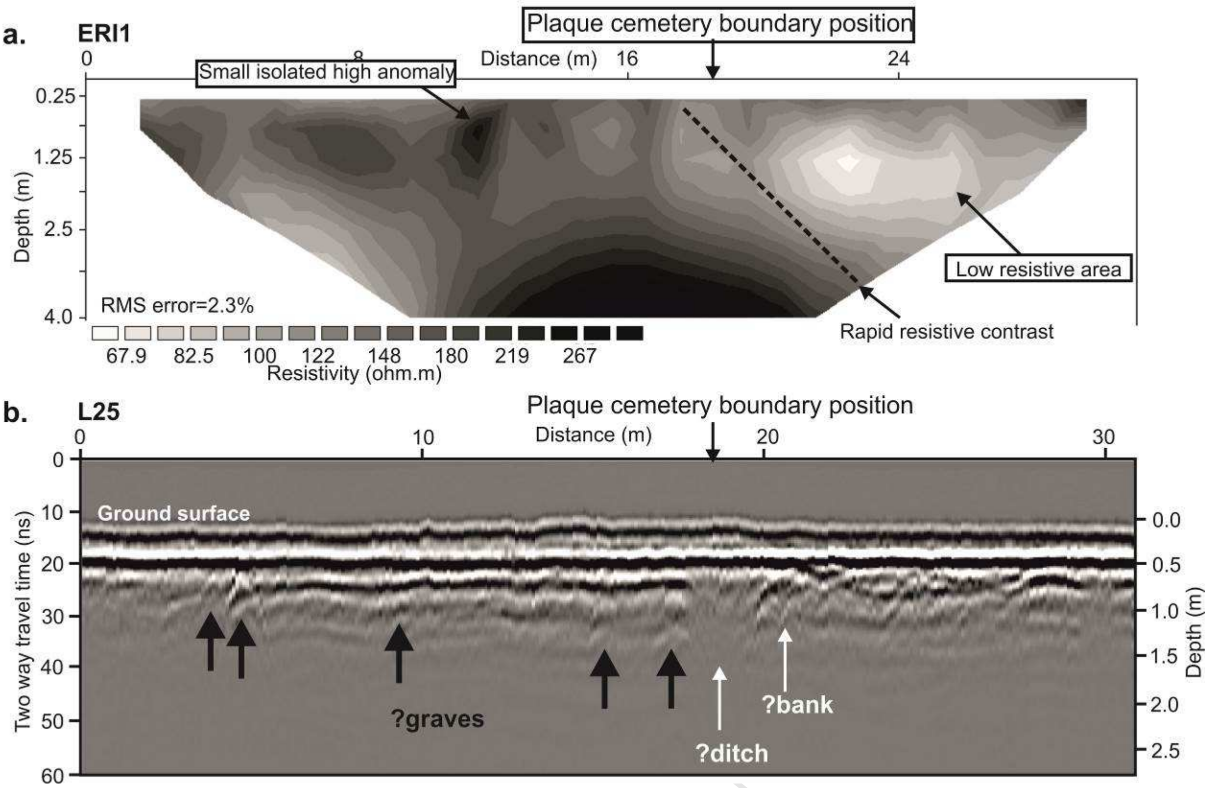


Figure 7: a) ERI1 and b) 2D GPR interpreted profile orientated west to east across the parish boundary (**Fig. 2** for location).



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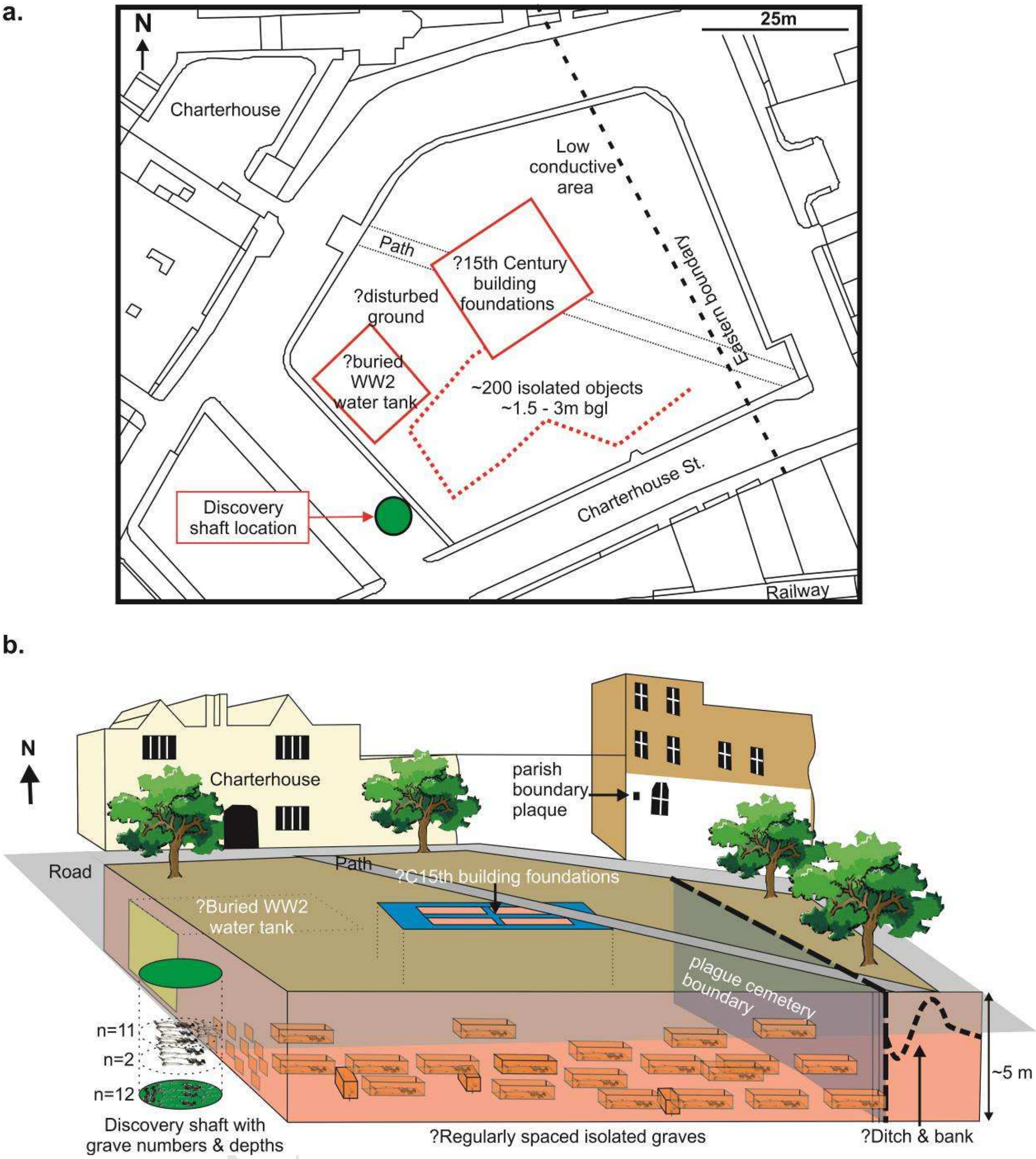


Figure 8: Summary showing geophysical interpretation, A) 2D Planview map and B) 3D schematic visualisation of the site that is not to scale.

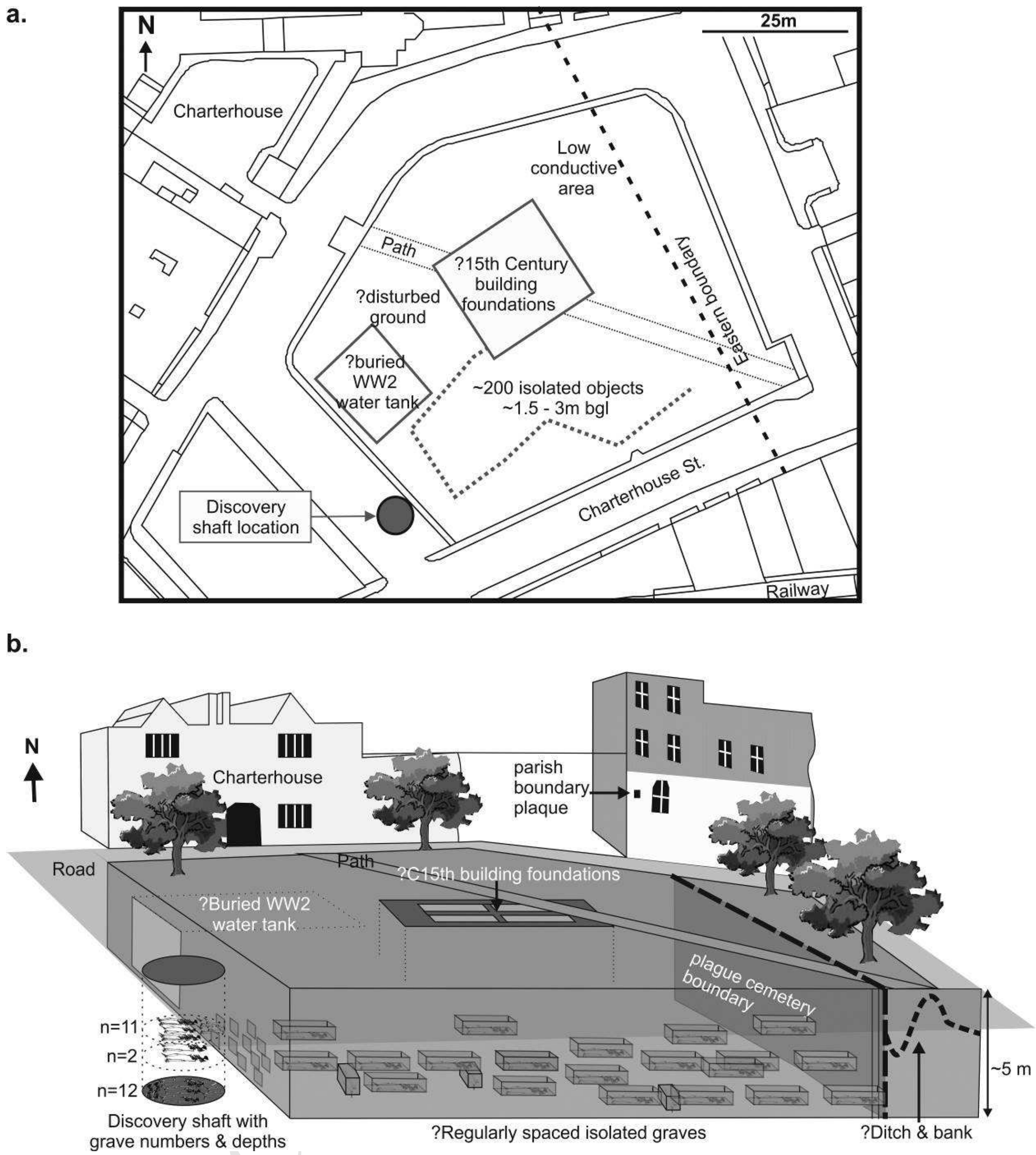


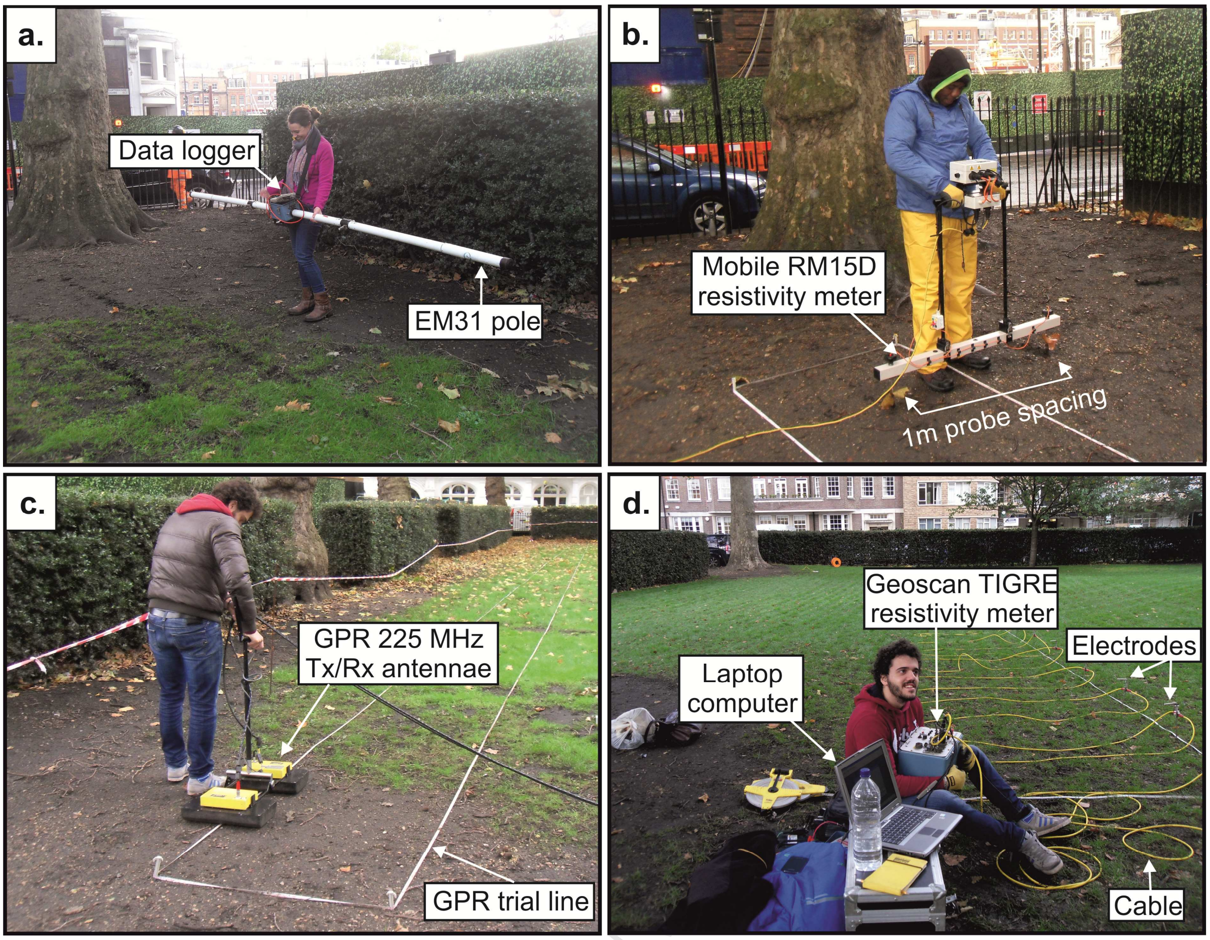
Figure 8: Summary showing geophysical interpretation, A) 2D Planview map and B) 3D schematic that is not to scale.

Site targets identified	Documented Records	Geophysical responses
Historic burials	Suggested burials in mass pits	GPR data imaged ~200 burials in SW of square, isolated, evenly spaced and ~1.5 m- 3 m bgl (Fig. 6/8)
Burial ground eastern boundary	Suggested parish boundary and ditch and bank form	2D ERI and GPR profiles (Fig. 7) agreed both boundary position and ditch and bank geometries
Demolished building foundations	Two chapels and meat kitchen recorded onsite	~20 m^2 square-shaped EM anomalies in central area (Fig. 4)
WW2 fire-fighting water tanks	Present 1940 but perhaps removed	~15 m^2 object in NW of square (Fig. 4), conductive, low resistance & strong horizontal top/base radar reflectors

Table 1. List of targets identified in this study, documented records and their geophysical responses (**Fig. 8** for location).

Highlights:

- Multiple skeletons discovered during Europe’s largest construction project
- Near-surface geophysical survey of Charterhouse Square revealed hundreds more
- Burials were surprisingly isolated and not in mass burial pits
- Burials were also phased and in different orientations
- Radiocarbon dating and aDNA tooth analysis confirmed Black Death victims
- Study has implications for other mass burial searches


a.
Data logger
EM31 pole
b.
Mobile RM15D
resistivity meter
1m probe spacing
c.
GPR 225 MHz
Tx/Rx antennae
GPR trial line
d.
Geoscan TIGRE
resistivity meter
Electrodes
Laptop
computer
Cable