Determining geophysical responses from burials in graveyards and cemeteries

Running Head: Geophysical responses from graves

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Abstract

Graveyards and cemeteries around the world are increasingly designated as full. There is therefore a requirement to identify vacant spaces for new burials or to identify existing ones to exhume and then re-inter if necessary. Geophysical methods offer a potentially non-invasive target detection solution; however, there has been limited research to identify optimal geophysical detection methods against burial age. This study has collected multi-frequency (225 MHz – 900 MHz) ground penetrating radar, electrical resistivity and magnetic susceptibility surface data over known graves with different burial ages and soil types in three UK church graveyards. Results indicate that progressively older burials are more difficult to detect but this decrease is not linear and is site specific. Medium-high frequency GPR and magnetic susceptibility was optimal in clay-rich soils, medium-high frequency GPR and electrical resistivity in sandy soils and electrical resistivity and low frequency GPR in coarse sand and pebbly soils respectively. A multi-geophysical technique approach should be utilised by survey practitioners where grave locations are not known to maximise target detection success. Grave soil and grave cuts are important grave position indicators. Grave headstones were not always located where burials were located. This study demonstrates the value of these techniques in grave detection and could potentially date burials from their geophysical responses.

Keywords: case history; gpr; electrical/resistivity; magnetic susceptibility

INTRODUCTION

Globally, church graveyards and cemeteries are suffering from a lack of burial space for new burials. With an estimated 55 million individuals needing to be buried each year (de Sousa, 2015), the problem is most acute in urban burial grounds that do not commonly re-use them. Burial area re-use varies between countries, for example, in Germany it is common to re-use existing burial areas after 25 years (see Fiedler et al. 2009), in the UK it is after 100 years (see Hansen et al. 2014), whereas for most US burial areas they are left in perpetuity (see Bigman 2012).

In the UK, only 25% of existing burial grounds have room to accept new burials (Hansen et al. 2014), and whilst 70% of current bodies are now cremated (Coutts et al. 2016), there still is not enough burial space (Hussein and Rugg, 2003). The re-use of existing burial grounds is one possible solution, for example, burial regulation relaxations of 0.4 m minimum burial depths have been in force in London since 2005 (Ministry of Justice, 2006). However, burial ground records, if available, rarely indicate burial positions, with grave headstones, if present, not always being in burial positions as Fiedler et al. (2009) documents. In order to determine the positions of unmarked burials, invasive probing methods (Owsley, 1995 for background) would not be appropriate due to religious and social sensitivities, and thus other detection technique(s) need to be considered.

Current search methods for terrestrial burials are varied and have been reviewed elsewhere (Pringle et al. 2012a), with best practice suggesting a phased approach, moving from remote sensing methods down to initial ground reconnaissance and trial surveys before full surveys are initiated (France et al., 1992; Larson et al., 2011). It is important to note that the search for unmarked graves in graveyards and cemeteries are usually quite different from clandestine graves of murder victims, as they are very different in terms of structure, burial depth below ground level of bgl (1m – 1.8 m compared to ~0.5 m respectively) and the complexity of burial contents (Fig. 1). Apart from graveyards and cemeteries being potentially reused and partially excavated, graves can also vary in style from earth-cut (as shown in Fig. 1) to brick-lined, and either coffined or not coffined (Hansen et al. 2014).

Figure 1. Here.

Remote sensing methods have been successfully used to identify unmarked clandestine burials (Davenport 2001). Ruffell et al. (2009) successfully identified historical (150-160 years old) unmarked cemetery graves using aerial photographs and confirmed positions by geophysical surveying. Remote sensing of geomorphology changes has also been utilised for successful detection of clandestine graves (Ruffell and McKinley, 2014) and localised vegetation growth that have different characteristics to background areas, for example, different species and with more or stunted growth when compared to surrounding areas (Dupras et al. 2011; Larson et al. 2011).

Geophysical detection techniques have also been shown to effectively detect graves. Ground penetrating radar (GPR) surveys have been the most widely-used, locating unmarked burials in graveyards and cemeteries with varying degrees of success (e.g. Vaughan, 1986; Nobes, 1999; Davis et al, 2000; Conyers, 2006; Fiedler et al. 2009; Hansen et al. 2014; Gaffney et al. 2015), and to search for both single and mass graves of homicide victims (Ruffell, 2005; Schultz 2007; Davenport 2011; Novo et al. 2011; Ruffell et al. 2014; Fernandez-Alvarez et al. 2016). Generally these researchers, and those undertaking modern control experiments (e.g. Schultz 2008; Schultz and Martin, 2011; 2012; Pringle et al. 2012b; 2012c; 2016; Molina et al. 2016), have suggested mid-range (200 MHz – 400 MHz) frequency antennae to be optimal to detect unmarked burials but this varies depending upon a host of specific site factors, including soil type, salinity, local depositional environment, burial ages, above-ground sources of interference, etc.

Electrical resistivity surveys have been used to locate unmarked burials in cemeteries (e.g. Matias et al. 2006; Hansen et al. 2014; Buyuksarac et al. 2015) and clandestine burials of homicide victims (Pringle and Jervis, 2010). Controlled experiments suggest that decompositional fluids may be the dominant factor in detecting graves with electrical geophysical methods (Jervis et al. 2009; Pringle et al. 2012b) and may be retained in grave soil for considerable periods of time after burial (Pringle et al. 2015a).

Electro-magnetic (EM) surveys have shown to have some success detecting unmarked burials in cemeteries (e.g. Nobes, 1999; Dionne et al. 2010; Bigman, 2012; Gaffney et al., 2015) and clandestine graves of homicide victims (Nobes, 2000), but control studies suggest that they are problematic in urban environments and in disturbed ground (Pringle et al. 2008).

Magnetic surveys for archaeological graves have shown to be successful (e.g. Powell, 2004; Stanger and Roe 2007; Gaffney et al. 2015) with magnetic susceptibility surface surveys being successful but rarely used (Linford, 2004; Pringle et al. 2015b).

There is, therefore, some information on the relative success rates of GPR, electrical resistivity and magnetic susceptibility methods to detect graves with different burial styles in graveyards and cemeteries (Fig.2). Table 1 summarises grave detection geophysical techniques against various burial ages, with consideration given for different soil types and local depositional environments. However, what is usually lacking is confirmation of what is causing anomalies in resulting datasets. Obtaining an accurate burial age of geophysical anomalies is crucial to determining which geophysical detection technique(s) is optimal for different-aged burials as well as determining optimal specific equipment configurations.

This paper aims are: *firstly* to detail results of geophysical investigations of marked graves in church graveyards with known burial dates; *secondly* determine the optimum geophysical detection method(s) and equipment configuration(s) of the different aged burials; and *thirdly* and finally, to gain knowledge of the effect of different soil types upon successful grave detection.

Figure 2. Here.

Table 1. Here

DATA ACQUISITION

Study sites

Three Church of England graveyards were selected for this study (Figs. 3-5). Each graveyard had known and accessible graves with headstones and burial ages ranging from the 19th century to the present day (Tables S1-S3). Graves able to be surveyed varied between sites; some could not be surveyed due to site constraints, proximity to objects or had surface obstructions. Surveys were undertaken in the autumn to reduce potential dataset variations due to changing climate, albeit one site (St. Michael's Church) was situated in the East of the UK that has comparatively less rainfall than Western areas. Respective parish church councils and their congregations had given their permission for the study.

The three graveyards also covered the major soil types found in the UK, confirmed by onsite auger surveys (Fig. S1). St. Michael and 'All Angels' Church in Norfolk, UK, has glacial till clay soil overlying Norwich Crag and Cretaceous Chalk bedrock (Fig. 3). St. John's Church in Staffordshire, UK, has sandy soil overlying Carboniferous Butterton Sandstone Formation bedrock (Fig. 4). St. Luke's Church in Staffordshire, UK has a coarse sandy-pebbly soil overlying Triassic Hawkesmoor Formation sandstones and conglomerate bedrock (Fig. 5).

Three trial survey lines were set out at each site adjacent to a row of selected headstones, orientated at right angles and at 0.5 m, 1 m and 1.5 m distance away from headstones, in order to determine the optimal survey line distance. Analysis of resulting data determined this to be 1 m, with respective dataset shown in Supplementary Material (Figs. S2-S3). The 0.5 m profile lines were probably picking up the headstones themselves, and the 1.5 m lines may have missed some grave positions.

Following the trials, further survey lines were positioned at all sites for geophysical datasets to be collected (Figs. 3-5). These were carefully chosen to maximise the number of graves to be surveyed, to cover a relatively wide burial age span at each survey site and to avoid potential interference; for example away from mature trees whose roots may cause effects and manmade structures such as churches and boundary walls. Twenty-six (2 min., 82 av., 214 max. years) graves were surveyed at St. Michael's of 'All Angels' church graveyard, Stockton, Norfolk, nineteen (13 min., 42 av., 100 max. years) graves at St. John's church graveyard, Keele, Staffordshire, and thirty-eight (1 min, 23 av., 42 max. years) graves at St. Luke's church graveyard, Endon, Staffordshire, (Tables S1-S3).

GPR surveys used SensorsandSoftware™ PulseEKKO 1000 equipment (Fig. 3) to collect 225 MHz, 450 MHz and 900 MHz central frequency, fixed-offset antenna datasets on both trial and full profiles at the study sites (Figs 3-5 and Tables S1-S3). The three central frequencies were chosen as they were deemed the most suitable, based on site soil types, trial profile data and target depths as others have shown (e.g. Hansen et al. 2014; Gaffney et al. 2015; Pringle et al. 2016). Both 110 MHz and 1,200 MHz antenna were not usable due to their large antenna size and time spent to collect data respectively. Respective GPR data acquisition specifications were: (i) 225 MHz 100 ns time window, 32 stacks and 0.1 m trace spacing, (ii) 450 MHz 80 ns time window, 32 stacks and 0.05m trace spacing; (iii) 900 MHz 60 ns time window, 32 stacks and 0.025m trace spacing.

Figure 3. Here.

Figure 4. Here.

Figure 5. Here

Electrical resistivity surveys used Geoscan™ RM15-D equipment (Fig. 4), using the typical dipole-dipole survey configuration, with fixed remote stainless steel electrode probes orientated along survey lines but sited at least ten times the distance of fixed-offset mobile probe spacings from profile ends to avoid remote probe effects (Milsom and Eriksen, 2011). Initial trials were also undertaken to determine the optimal mobile electrode probe fixed-offset spacing; results suggested this was 0.5 m spacing (as opposed to 0.25 m or 1 m) as this dataset showed the clearest anomalies over known burial positions, with respect to background values (Fig. S4). This was surprising as penetration depths should not be enough to image the graves itself; they may be imaging the grave soil (Fig. 1a). Analysis of trial data also observed that sample point spacings along respective survey lines could be at 0.1 m intervals which collected enough data points to image the known grave positions when compared to background values (Fig. S4).

Magnetic susceptibility surface data used a Bartington™ MS-2D field coil susceptibility meter connected to a laptop using Bartsoft™ v.4 data acquisition software (Fig. 5). A 0.3 m diameter surface probe with a stated 1 m penetration depth generated a sample measurement (set at 1 s throughout) when placed on the ground at each sampling point and repeated three times, with a profile line sampling interval of 0.1 m. After every 5 sampling points, the probe was raised to calibrate the instrument (zeroed) and to measure equipment drift during data acquisition. This data acquisition protocol has successfully been used in related studies to identify unmarked burials (Pringle et al. 2015b).

DATA PROCESSING

For GPR data, standard processing steps (e.g. Cassidy, 2009; Reynolds, 2011) were undertaken on the downloaded 2D profiles in REFLEX-Win v.8 software which were: (i) removal of blank data; (ii) first arrival digitally picked and shifted to 0 ns to ensure consistent arrival times; (ii) 1D dewow filter applied; (iv) AGC gain filter; (v) time-cut to clip blank data at base of profiles; and finally; (vi) time-depth conversion using site averages of both common-mid point (CMP) survey data obtained onsite and site diffractions (calculated, on average, to be ~0.08 m/ns for St. Michael's Church clay-rich soil graveyard, Stockton, Norfolk, ~0.082m/ns for St. John's Church sandy-rich soil graveyard, Keele, Staffordshire and ~0.075 m/ns for St. Luke's Church sandy-pebbly soil graveyard, Endon, Staffordshire respectively). Further advanced processing steps (such as migration) was not necessary as these are not commonly performed in forensic geophysical surveys and thus hyperbolic reflection target events were needed to be imaged.

For electrical resistivity data, standard processing steps (e.g. Milsom and Eriksen, 2011) were undertaken on the downloaded data which were: (i) conversion of measured resistance (Ω) values to apparent resistivity (Ω.m) to account for respective probe spacing configurations; (ii) data de-spiking to remove anomalous isolated data points (averaging 3% of data); (iii) each profile having a linear trend fitted to respective data and then used to detrend profiles to remove long wavelength site trends to allow smaller, grave-sized features to be more easily identified and interpreted and; (iv) graphical plotting to allow data comparison. For the resistivity trial at St. Johns, the three profiles acquired over survey line 1 were instead; (iii) imported into Generic Mapping Tools (GMT) software, and; (iv) a minimum curvature gridding algorithm was used to digitally contour a surface onto measurement positions, before; (v) detrending by fitting a cubic surface to the data and then subtracting this surface and finally; (vi) normalising the datasets by subtracting their respective mean values and plotting in standard deviation units. Respective dataset statistics are presented in Table 2.

For magnetic susceptibility data, standard processing steps (e.g. Milsom and Eriksen, 2011) were undertaken on the downloaded data which were: (i) re-ordering data to correct spatial positions on survey profile lines; (ii) averaging the three measurements per sample position; (iii) data de-spiking to remove anomalous isolated data points (averaging 5% of data); (iv) each profile having a linear trend fitted to respective data and then used to detrend profiles to remove long wavelength site trends to allow smaller, grave-sized features to be more easily identified and interpreted and; (v) graphical plotting to allow data comparison. Respective dataset statistics are shown in Table 2.

Table 2. Here.

RESULTS

For GPR 2D profiles, where isolated half-hyperbolic reflection events had significant signal amplitudes and were clearly visible, these positions were identified, correlated with burial headstone positions and numbered (Tables S1-S3). For both magnetic susceptibility and apparent resistivity 2D datasets, isolated anomalies, with multiple data points and a ±1SD from background values, were identified and again correlated with burial headstone positions and numbered (Tables S1-S3).

At St. Michael of All Angels' clay-rich soil graveyard in Stockton, Norfolk, GPR results showed 900 MHz frequency antennae were optimal. For example, on survey line 2, 225 MHz dominant frequency identified only 1 (G18) out of 9 graves, the 450 MHz dominant frequency detected 8 out of 9 graves, and the 900 MHz dominant frequency detected all 9 and indeed 2 unmarked graves as hyperbolic reflection events (Fig. 6 and Table S1). The numerous small GPR 900 MHz anomalies, associated with grave positions, may have been picking up the 'grave cut' (Fig. 1) or small objects within the grave soil rather than the grave itself, as signal attenuation would result in reduced penetration depths using this frequency. GPR profiles also imaged a horizontal slab (Fig. 2c-e) on survey line 3 (Fig. 7). Magnetic susceptibility data was more variable; it did not detect the oldest graves but did detect more recent ones as relatively high magnetic anomalies, when compared to background values (Fig. 6 and Table S1). Resistivity surveys were also relatively successful over recent burials, detected as areas of relative low resistivity anomalies when compared to background values, although these were less strong for progressively older burials (Fig. 6 and Table S1).

Figure 6: Here. **Figure 7**: Here.

At St. John's Church sandy soil graveyard in Keele, Staffordshire, GPR results showed 450 MHz frequency antennae were optimal. For example, on survey line 2, GPR 225 MHz dominant frequency data only identified 1 out of 4 graves, with both 450 MHz dominant frequency data and 900 MHz dominant frequency data detecting all 4 (Table S2). Interestingly GPR profile line 4 showed a double burial (G19) that was not positioned vertically (Fig. 8). Magnetic susceptibility detected most graves as relatively high magnetic anomalies when compared to background values, although there were also some headstone positional errors when compared to burial positions. Resistivity surveys were less successful at detecting anomalies that could be correlated to burial headstone positions.

Figure 8: Here.

At St. Luke's Church sandy-pebbly soil graveyard in Endon, Staffordshire, GPR results indicated that 225 MHz frequency antennae were optimal (Figs. S18-S19 and Table S3). Magnetic susceptibility detected most graves although they were relatively young, as anomalies being relatively low, compared to background values, in contrast to the first two case studies (Fig. 9). Resistivity surveys detected most graves with anomalies being relatively low compared to background values (Fig. 9 and Table S3).

Figure 9. Here.

It was not possible to quantify the quality of GPR anomalies over known grave positions. Seismic semblance analysis methods has been used on GPR anomalies over simulated clandestine graves (Booth and Pringle, 2016), but in this dataset the many minor anomalies present was too problematic. Instead a four-fold qualitative *Excellent, Good, Poor and None* grade was given for known grave positions in the three graveyards, based on a visual comparison of anomalies as detailed by Schultz and Martin (2012). *Excellent* and *Good* refers to very clear and clear hyperbolic reflection events being imaged respectively, *Poor* refers to just discernible hyperbolic reflection events being imaged and *None* refers to no anomalies being imaged at known grave locations. Other authors have used this method on forensic geophysical datasets (Pringle et al. 2016). The anomaly ranking method has been undertaken; results are in Tables 5-7 for St. Michael's, St. Johns' and St. Luke's Church study sites respectively.

It was also difficult to quantify the magnetic susceptibility and electrical resistivity anomalies observed over known grave positions. Whilst results were numerical and despiking and detrending had been performed, results had widely varying anomalies over known grave positions, both in amplitude and whether being an anomalous low or high when compared to background values (*cf.* Figs. 6 and 9). The resulting geophysical anomalies also widely varied in amplitude when comparing between the study sites and between survey profiles within the same study site (Table 2). Therefore, the four-fold qualitative *Excellent*, *Good*, *Poor* and *None* grade, used to rank the GPR anomalies over known grave positions was used for these datasets as well (Tables 3-5).

Table 3. Here.

Table 4. Here

Table 5. Here

DISCUSSION

The first aim of this paper was "*to detail results of geophysical investigations of marked graves in church graveyards with known burial dates"*. Geophysical responses observed over burial positions does seem to decrease as burial age increases (Tables 3-5). This would be logical, once the grave soil is compacted and skeletonization is complete, together with degradation of coffins and associated trappings (McGowan and Prangnell, 2015), it would make geophysical targets more difficult to identify. One of the main geophysical targets in graveyard surveys is the back-filled shaft filled with disturbed soil (Fig. 1) that would rapidly compact over time, and would therefore have little geophysical contrast when compared with undisturbed background soil after significant burial ages. This both confirms and extends results of shorter-term (6 year) controlled clandestine burial studies (e.g., Schultz, 2008; Schultz and Martin, 2011; 2012; Pringle et al. 2012b; Pringle et al. 2016; Molina et al. 2016), although, of course, simulated burials were much shallower and without funerary impedimenta such as coffins. However, as burial ages are known, cross-plots of geophysical responses versus burial ages have been generated that did not always show a decreasing linear relationship as burial age increases (Fig. 10 and S22-S24). Whilst relatively young burials (<30 years old) tended to have a geophysical response forming a decreasing linear trend (Fig. 10a), over longer periods this relationship appeared to be more logarithmic (Fig. 10b). GPR data results, in particular, seem to be more variable, with some old burials still imaged, as other researchers have found over historical burials grounds (e.g. Davis et al. 2000; Hansen et al. 2014; Gaffney et al. 2015; Dick et al. 2015).

Figure 10. Here.

The second aim of this paper was "*to determine the optimum geophysical detection method(s) and equipment configuration(s) of the different aged burials*".

For GPR surveys, the most popular technique in forensic geophysics (e.g. Vaughan, 1986; Nobes, 1999; Davis et al, 2000; Conyers, 2006; Fiedler et al. 2009; Novo et al. 2011; Pringle et al. 2012; Hansen et al. 2014; Ruffell et al. 2014; Gaffney et al. 2015; Fernandez-Alvarez et al. 2016), suggested best practice is to use mid-range frequency antennae for surveys. From this study results, relatively high (900 MHz) frequency were optimal for grave detection in clay- and sand-rich soils whereas low frequency (225 MHz) frequency was optimal in sandy-pebbly soils. 900 MHz anomalies were mostly shallow responses, which may be recording the grave cut, small objects in the disturbed grave soil, or even headstone bases, but some unmarked graves without headstones were also detected so caution must be applied to such near-surface anomalies. Clearly smaller trace spacings for all frequency antenna will improve target resolution as more data is collected over each target grave, but this will increase survey time. It is deemed doubtful that 900 MHz frequency data will penetrate to the typical 1.8 m target depths bgl (Fig. 1); either the grave headstone is imaged or, perhaps, multiple occupancy target graves are being imaged.

For magnetic susceptibility surveys, grave locations were generally detected as relatively high magnetic susceptibility anomalies, compared to background values, as others have shown (e.g. Linford, 2004; Pringle et al. 2015). In St. Michael's clay-rich soil graveyard in Norfolk, they were more successful than electrical resistivity surveys. 0.1 m spaced sampling positions were optimal for grave detection.

For electrical resistivity surveys, grave locations were generally detected as relatively low resistance compared to background values, as others have found (e.g. Matias et al. 2006; Hansen et al. 2014; Buyuksarac et al. 2015), and was found to be optimal in St. Luke's sandy-pebbly soil graveyard. However, burial style can give important variations. 0.5 m fixed-offset mobile probe spacing was optimal for grave detection when tested against 0.25 m and 1 m fixed-offset spacings. These may not be imaging the grave itself but rather the respective target grave soil (Fig. 1).

Study outcomes suggest a multi-technique forensic geophysical survey be undertaken when looking for unmarked burials in church graveyards and cemeteries. Having more than one technique improves target detection success rates, with, for example, at St. Michael's church clay-rich soil graveyard in Stockton, Norfolk, only 2 (G5 and G6) of the oldest known graves were not imaged by either GPR or magnetic susceptibility, whereas using one technique would only give 72% and 59% detection rates respectively (Table 3). At St. John's Church sandy soil graveyard, techniques seem to be less complementary; high frequency GPR data was optimal, with others not detecting the remainder (Table 4). At St. Luke's church pebbly-sandy soil graveyard, Endon, Staffordshire, results showed electrical resistivity surveys were optimal, magnetic susceptibility surveys should be the complementary technique as this was more successful than GPR datasets (Table 5).

The third, and final, aim of this paper was "*to gain knowledge of the effect of different soil types upon successful grave detection*".

When factoring out similar-aged graves and equipment configurations, different techniques (or indeed a combination) still proved most effective and, as such, clearly soil type was the major variable for target detection success (*cf.* Tables 3-5). Other authors (e.g. Nobes, 1999; Ruffell et al. 1999) have also found widely varying target detection results, depending upon soil type. Interestingly electrical resistivity surveys, for example at St. Luke's Church sandy-pebbly soil graveyard in Staffordshire, were 40% more likely to detect graves than GPR. This therefore suggests electrical resistivity surveys be undertaken in sandy-pebbly soils to maximise grave detection.

Soil type will also have an impact as different soils have widely different porosities and hence corresponding soil moisture contents, local climate effects, decomposition rates, etc. Just using electrical resistivity as an example, in clay-rich soils, any grave fluid (Fig. 1) will be retained within the grave, whereas in sandy soils this will spread much further and predominantly by gravitational processes (Pringle et al. 2015); this is actually beneficial as it will create a larger if more diffuse target area to be geophysically detected.

CONCLUSIONS

Selected known grave positions and burial ages (0-214 years) in three Anglican Church graveyards, with varying soil types, were geophysically surveyed using multi-frequency GPR, electrical resistivity and surface magnetic susceptibility techniques. Target detection decreased as burial age increased; however, results showed that soil type was the major variable. In clay-rich soil 900 MHz frequency GPR data was optimal, followed by 450 MHz frequency, then magnetic susceptibility and electrical resistivity. In sandy-rich soil 900 MHz frequency GPR data was optimal, followed by 450 MHz frequency, then electrical resistivity and magnetic susceptibility/225 MHz frequency GPR. Finally, for sandy-pebbly soil electrical resistivity was optimal, followed by magnetic susceptibility, 225 MHz and 450 MHz frequency GPR data. For survey configurations, 0.1 m-spaced sample positions were enough for target detection, with 0.5 m spaced fixed-offset electrode probes found to be optimal for electrical resistivity surveys

Therefore using more than one geophysical survey technique is recommended, with combined GPR, electrical resistivity and magnetic susceptibility surveys producing the best results when target positions are not known in existing graveyards and cemeteries.

Study results also show that known grave marker positions may not be always accurate. Increasing the numbers of surveyed graves would provide more confidence of results, but this was not possible due to the graveyards surveyed and above-ground materials present. More graveyards with different soil types would validate and improve study results, for example, peat-rich soils, saline coastal soils, etc. Other burial grounds in different climates and depositional environments would also be helpful to survey and compare to these datasets. It would also prove useful to survey burials from other religious faiths, or indeed so-called green burials to see what effect different burial styles have on target detection.

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Figure Captions:

Figure 1. Generalised schematic figures of (a) isolated graveyard/cemetery burial showing typical geophysical targets, including back-fill 'grave' soil, coffin/contents and 'grave soil water fluid', and contrasting with typical clandestine grave of homicide victim with relative (b) early and (c) late stage decomposition and potential grave indicator markers/targets. Targets include the grave cut, disturbed ground, gases, grave soil water and variable vegetation (after Pringle et al. 2012a).

Figure 2. Generalised schematic of burial styles encountered in graveyards and cemeteries: (a) isolated earth-cut grave with common wooden (or rarely metal or lead-lined) coffin; (b) inter-cut/ overlying earth-cut graves with common wooden coffins; (c) brick-lined and top slab (black arrows) grave with single wooden coffin and some soil infill; (d) brick-lined and top slabbed (black arrows) grave with stacked wooden coffins; (e) brick-lined and top slabbed vault (black arrows), partitioned with multiple wooden/stone/lead-lined coffins (electrode probes not able to penetrate) and; (f) so-called green with wicker coffin, rapidly dug with/without wooden coffin and nomadic graves that may have wrapped/unwrapped remains respectively. These then have their typical (top) electrical resistivity, (middle) magnetic susceptibility and (bottom) GPR 2D profile anomalies (white arrows) geophysical responses. Top schematic from Hansen et al. (2014).

Figure 3. Sitemap of St. Michael's of All Angels church clay-rich soil graveyard, Norfolk, UK, (location inset), showing 225 MHz frequency GPR data being collected, surveyed profile lines and orientations, numbered Grave (Table S1) positions and annotated site

photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

Figure 4. Sitemap of St. John's church sandy loam soil graveyard, Keele, Staffordshire (location inset), UK, showing electrical resistivity data being collected, surveyed profile lines and orientations, numbered Grave (Table S2) positions and site photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

Figure 5. Sitemap of St. Luke's church sandy-pebbly soil graveyard, Endon, Staffordshire (location inset), UK, showing magnetic susceptibility data being collected, surveyed profile lines and orientations, numbered Grave (Table S3) positions and annotated site photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

Figure 6: St. Michael's church clay-rich soil graveyard survey line 2 (Fig. 3 for location), Norfolk, showing grave locations represented by headstones with year of burial inset, (a) 225 MHz, (b) 450 MHz and, (c) 900 MHz frequency 2D GPR profiles, (d) magnetic susceptibility and (d) apparent resistivity profile with interpreted (arrow) burials (Table S1).

Figure 7: St. Michael's church clay-rich soil graveyard survey line 3 (Fig. 3 for location), Norfolk, showing, grave locations represented by headstones with year of burial inset, (a) 225 MHz, (b) 450 MHz and, (c) 900 MHz frequency 2D GPR profiles with interpreted (arrow) burials (Table S1). Note marked horizontal slab (schematically shown in Fig. 2c-e).

Figure 8: St. John's church sandy-rich soil graveyard survey line 4 (Fig. 4 for location), Staffordshire, showing grave locations represented by headstones with year of burial (inset), (b) 225 MHz and (c) 450 MHz frequency 2D GPR profiles with marked interpreted burial (Table S2) positions; white arrow depicts shallower burial is offset to a deeper one (see text).

Figure 9. St. Luke's church sandy-pebbly soil graveyard survey line 2 (Fig. 5 for location), Staffordshire, showing grave locations represented by (a) headstones with year of burial inset, (b) magnetic susceptibility and (c) apparent resistivity profile position with marked interpreted burial (Table S3) position.

Figure 10. Cross-plots of geophysical responses versus burial age obtained in this study. (a) Survey line 2 (with statistically significant linear trend) of apparent resistivity response versus burial age (Table S1) at St. Michael of All Angels Church clay-rich soil, Stockton, Norfolk, UK. (b) All magnetic susceptibility study qualitative ranking results (see text) versus burial age with general trend, compiled from Tables 3-5.

Table Captions:

Table 1. Generalised table to indicate potential of geophysical techniques success for grave(s) location assuming optimum equipment configurations. Note this table does not differentiate between target size, burial depth and other important specific factors (see text). Key: ◐ Good; ● Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types. Modified from Pringle and others (2012a).

Table 2. Summary statistics (minimum/average/maximum/SD) of respective resistivity and magnetic susceptibility survey line and datasets collected from the three study sites.

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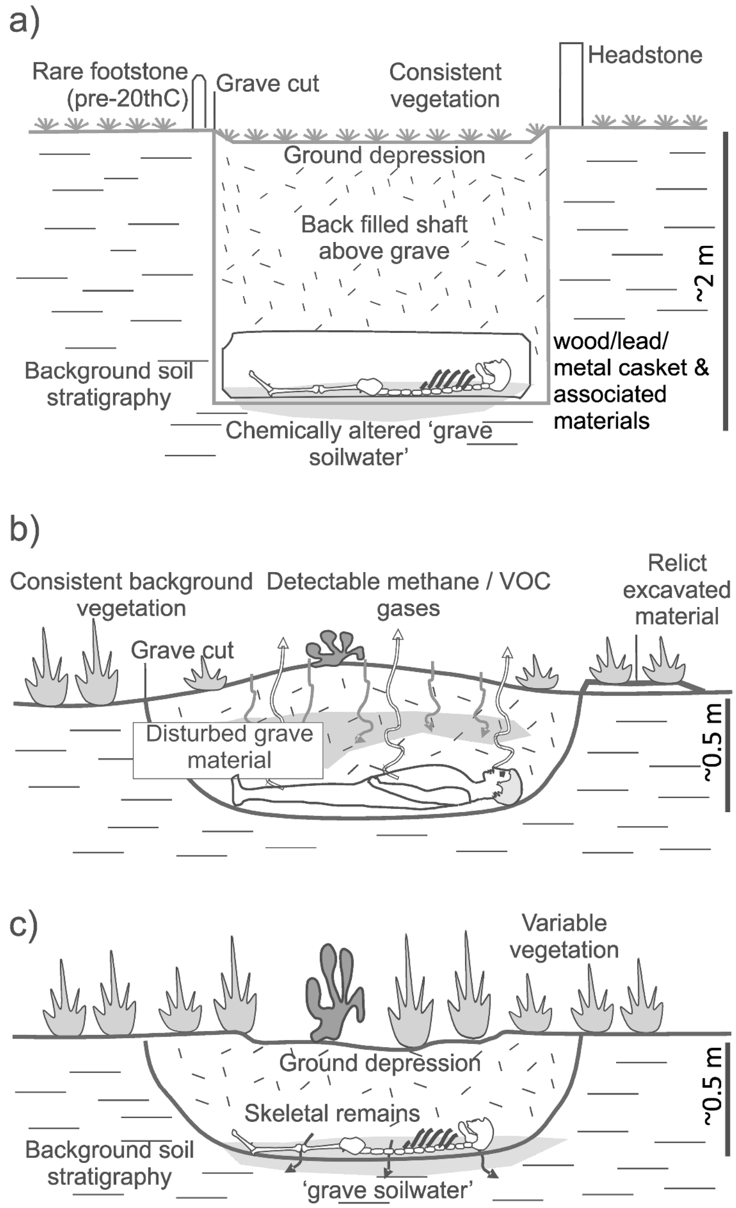
Table 4. Summary of grave detection (ordered in burial age) by geophysical methods at St. John's sandy soil graveyard, Staffordshire, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None (as defined by Schultz and Martin 2012).

Table 5. Summary of grave detection (ordered in burial age) by geophysical methods at St. Luke's sandy-pebbly soil graveyard, Staffs, UK, using the qualitative ranking system of Excellent, Good, Poor and None anomalies (as defined by Schultz and Martin 2012).



1.

Figure 1. Generalised schematic figures of (a) isolated graveyard/cemetery burial showing typical geophysical targets, including back-fill 'grave' soil, coffin/contents and 'grave soil water fluid', and contrasting with typical clandestine grave of homicide victim with relative (b) early and (c) late stage decomposition and potential grave indicator markers/targets. Targets include the grave cut, disturbed ground, gases, grave soil water and variable vegetation (after Pringle et al. 2012a).

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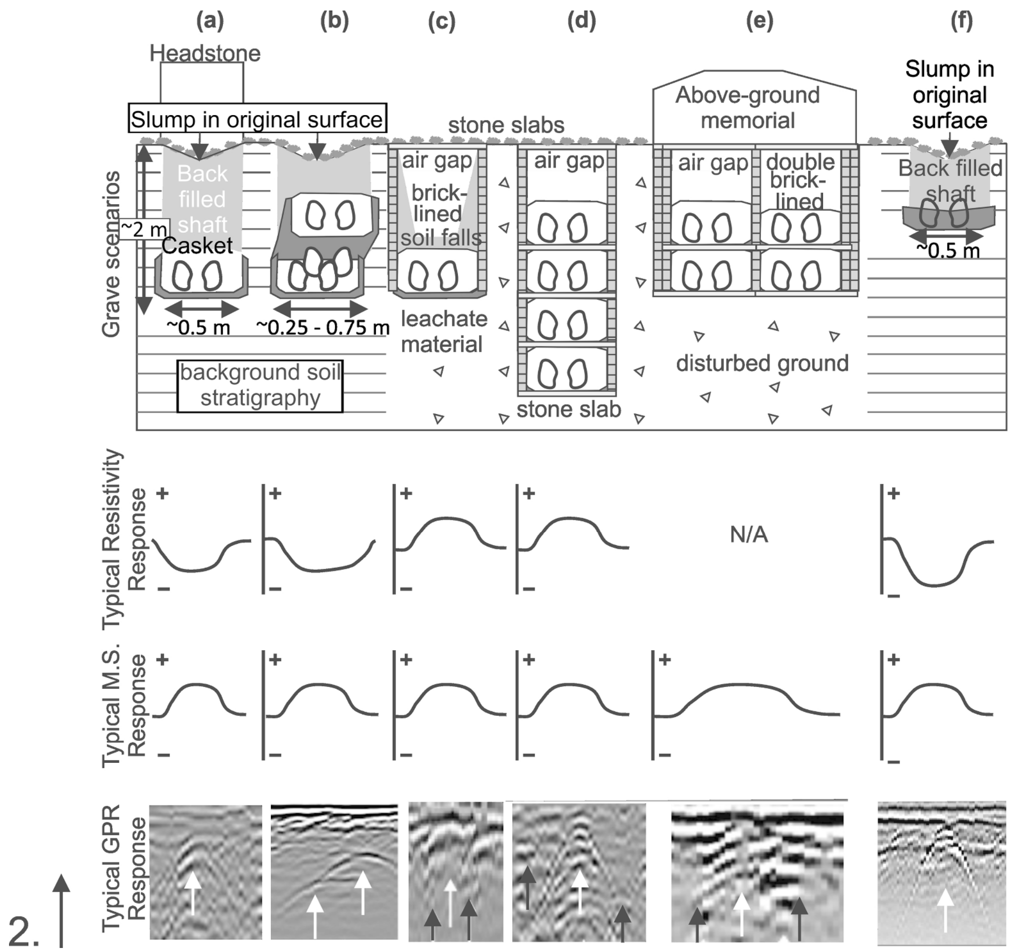

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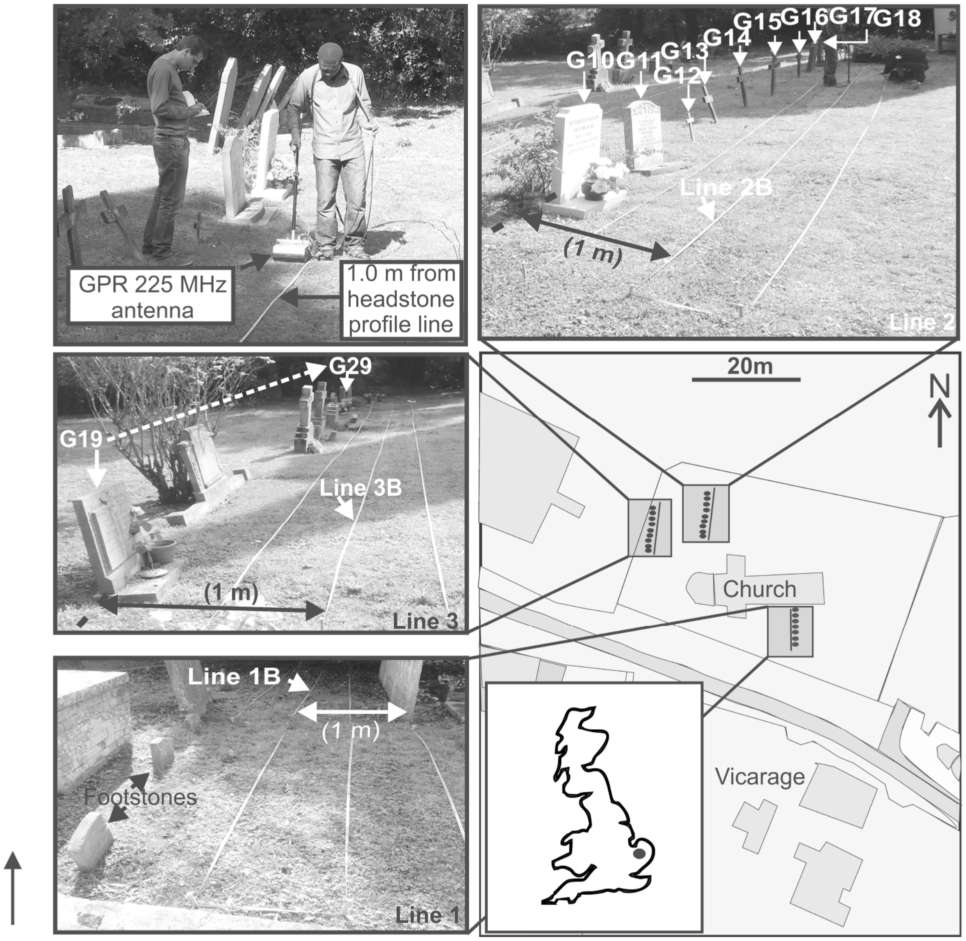


3.

Figure 3. Sitemap of St. Michael's of All Angels church clay-rich soil graveyard, Norfolk, UK, (location inset), showing 225 MHz frequency GPR data being collected, surveyed profile lines and orientations, numbered Grave (Table S1) positions and annotated site photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

114x106mm (600 x 600 DPI)

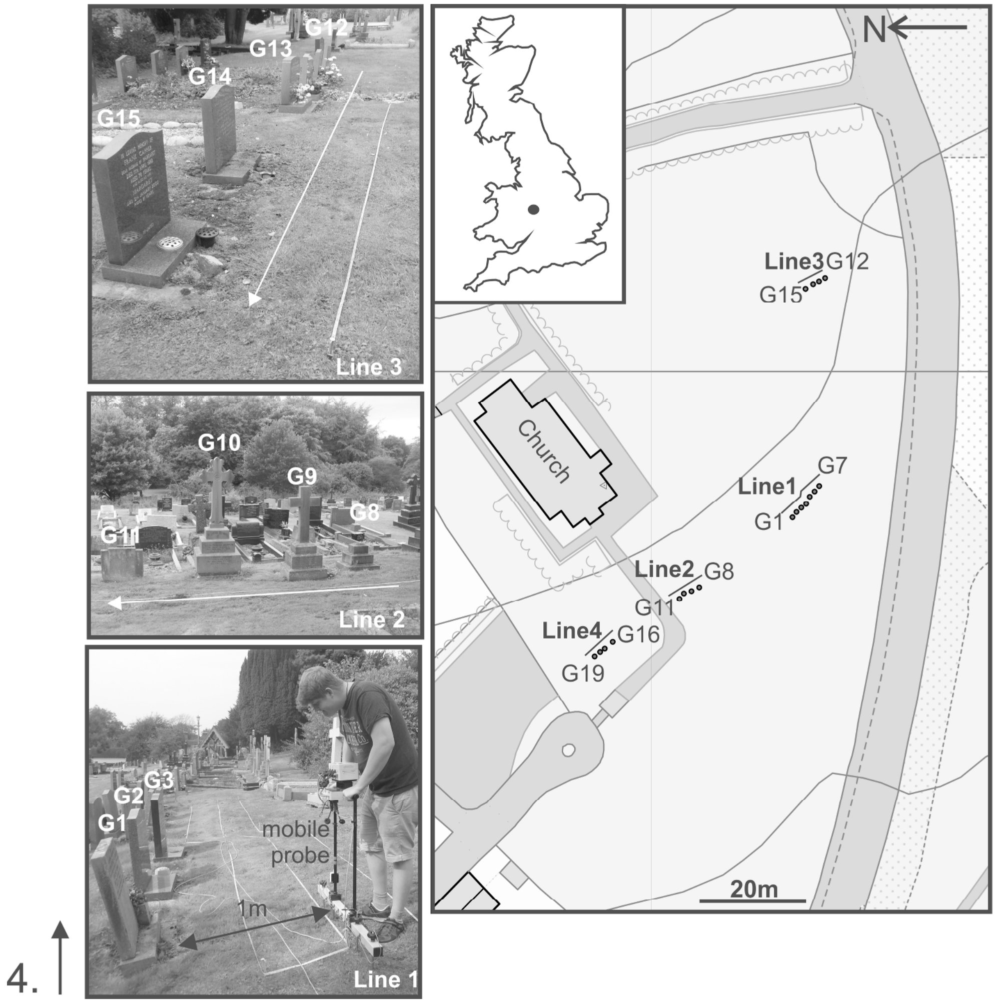


Figure 4. Sitemap of St. John's church sandy loam soil graveyard, Keele, Staffordshire (location inset), UK, showing electrical resistivity data being collected, surveyed profile lines and orientations, numbered Grave (Table S2) positions and site photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

121x120mm (600 x 600 DPI)

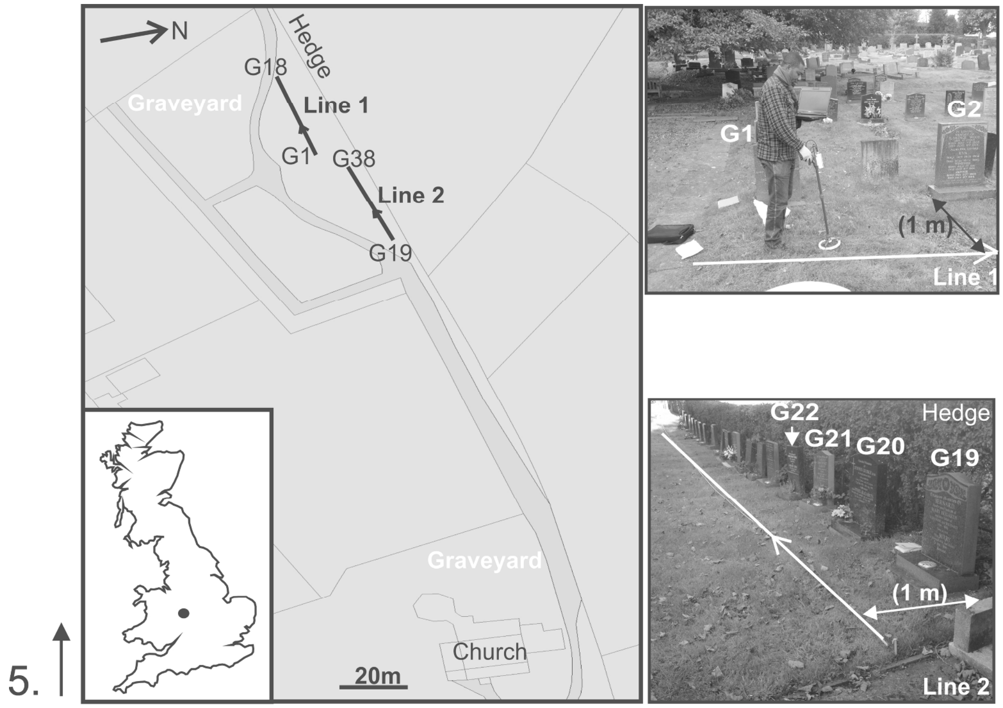
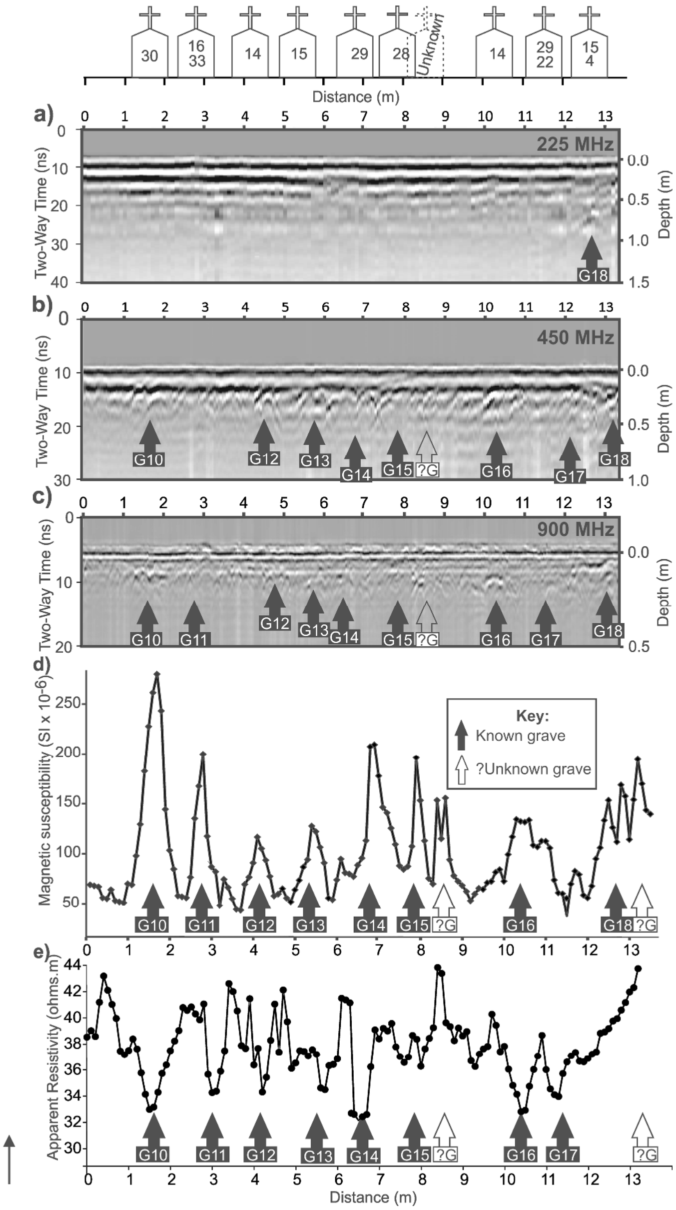


Figure 5. Sitemap of St. Luke's church sandy-pebbly soil graveyard, Endon, Staffordshire (location inset), UK, showing magnetic susceptibility data being collected, surveyed profile lines and orientations, numbered Grave (Table S3) positions and annotated site photographs. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

119x117mm (600 x 600 DPI)



6.

Figure 6: St. Michael's church clay-rich soil graveyard survey line 2 (Fig. 3 for location), Norfolk, showing grave locations represented by headstones with year of burial inset, (a) 225 MHz, (b) 450 MHz and, (c) 900 MHz frequency 2D GPR profiles, (d) magnetic susceptibility and (d) apparent resistivity profile with interpreted (arrow) burials (Table S1).

219x376mm (600 x 600 DPI)

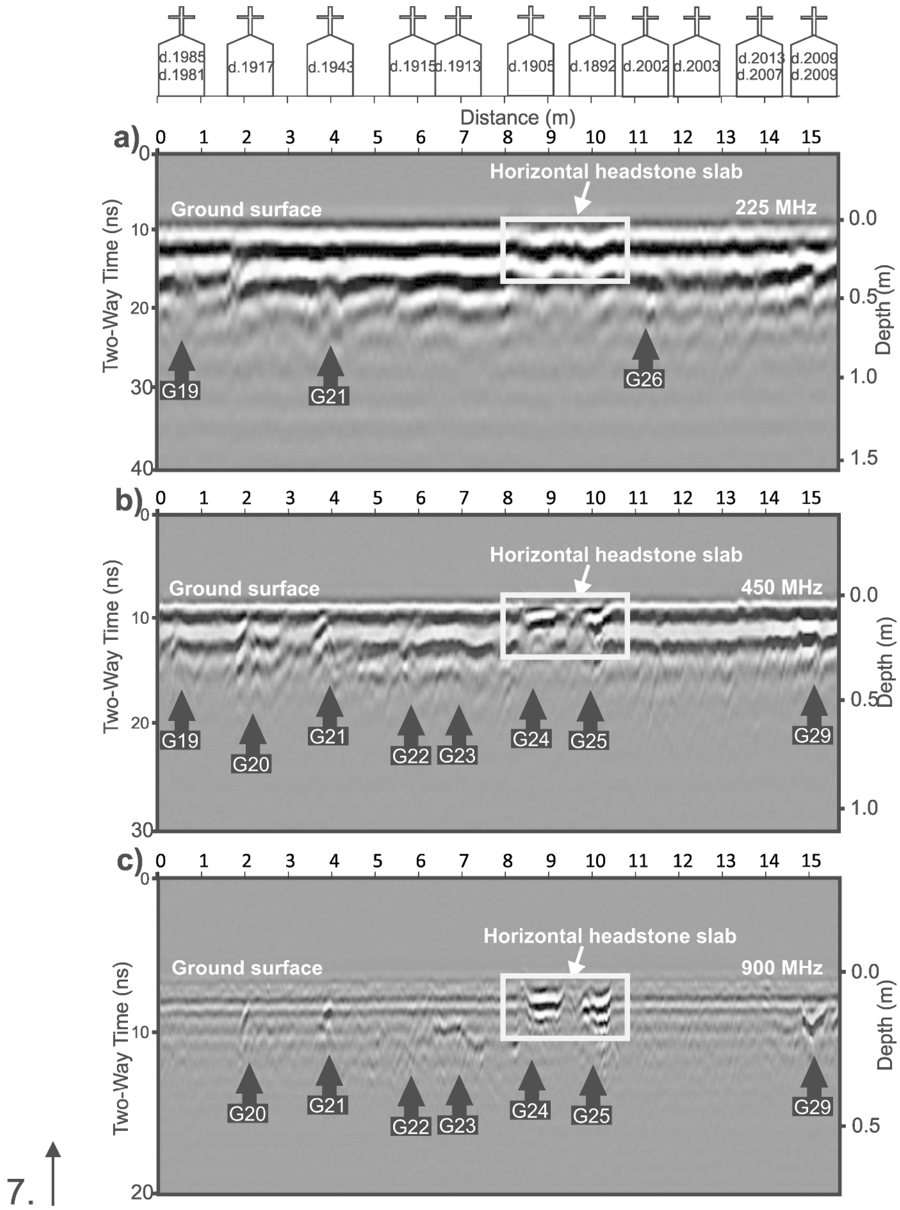


Figure 7: St. Michael's church clay-rich soil graveyard survey line 3 (Fig. 3 for location), Norfolk, showing, grave locations represented by headstones with year of burial inset, (a) 225 MHz, (b) 450 MHz and, (c) 900 MHz frequency 2D GPR profiles with interpreted (arrow) burials (Table S1). Note marked horizontal slab (schematically shown in Fig. 2c-e).

166x225mm (600 x 600 DPI)

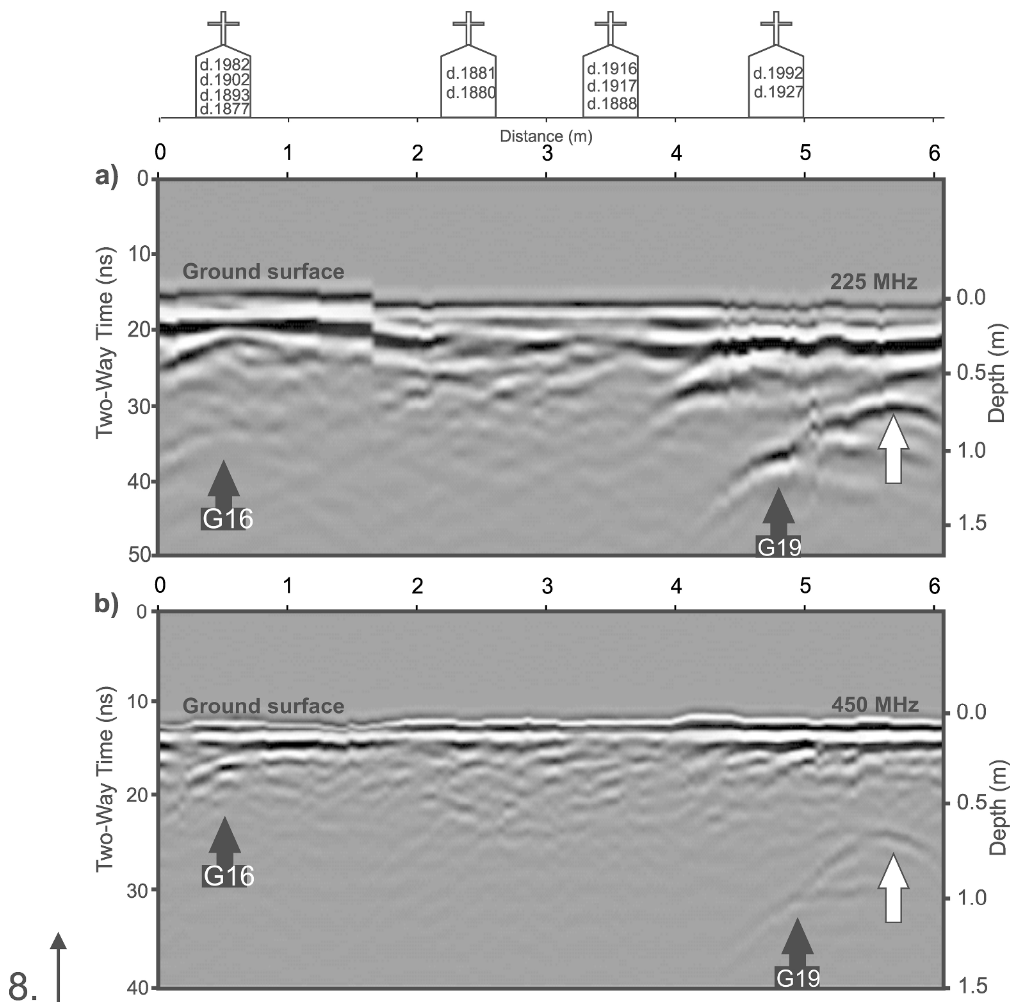


Figure 8: St. John's church sandy-rich soil graveyard survey line 4 (Fig. 4 for location), Staffordshire, showing grave locations represented by headstones with year of burial (inset), (b) 225 MHz and (c) 450 MHz frequency 2D GPR profiles with marked interpreted burial (Table S2) positions; white arrow depicts shallower burial is offset to a deeper one (see text).

128x127mm (600 x 600 DPI)

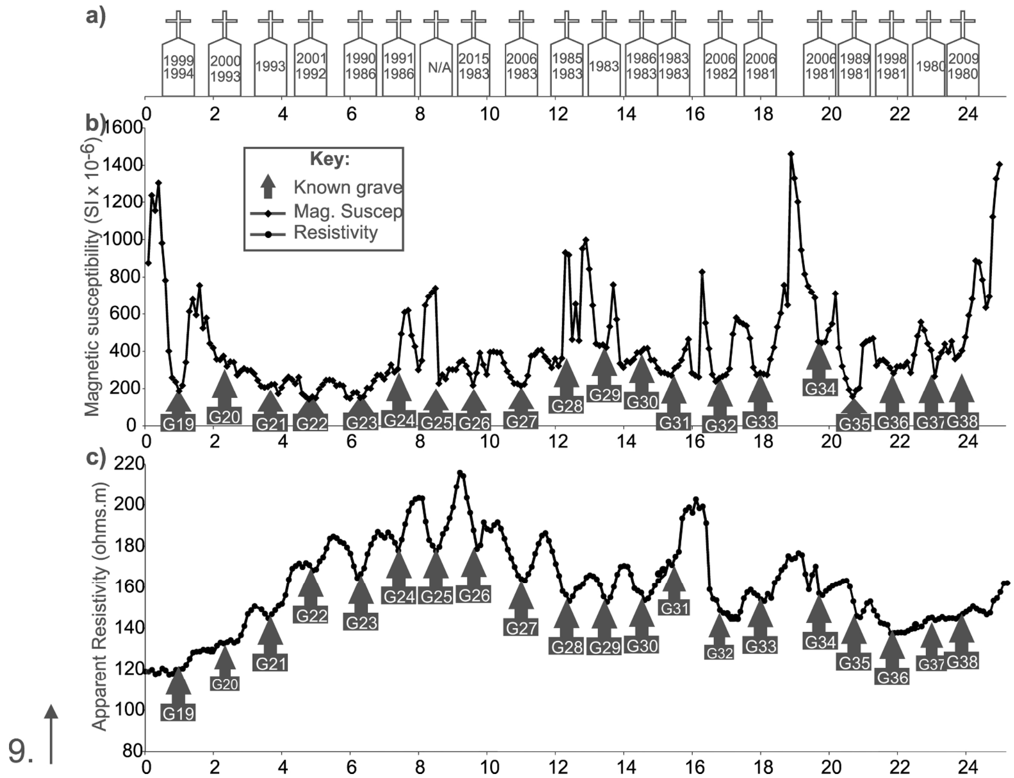
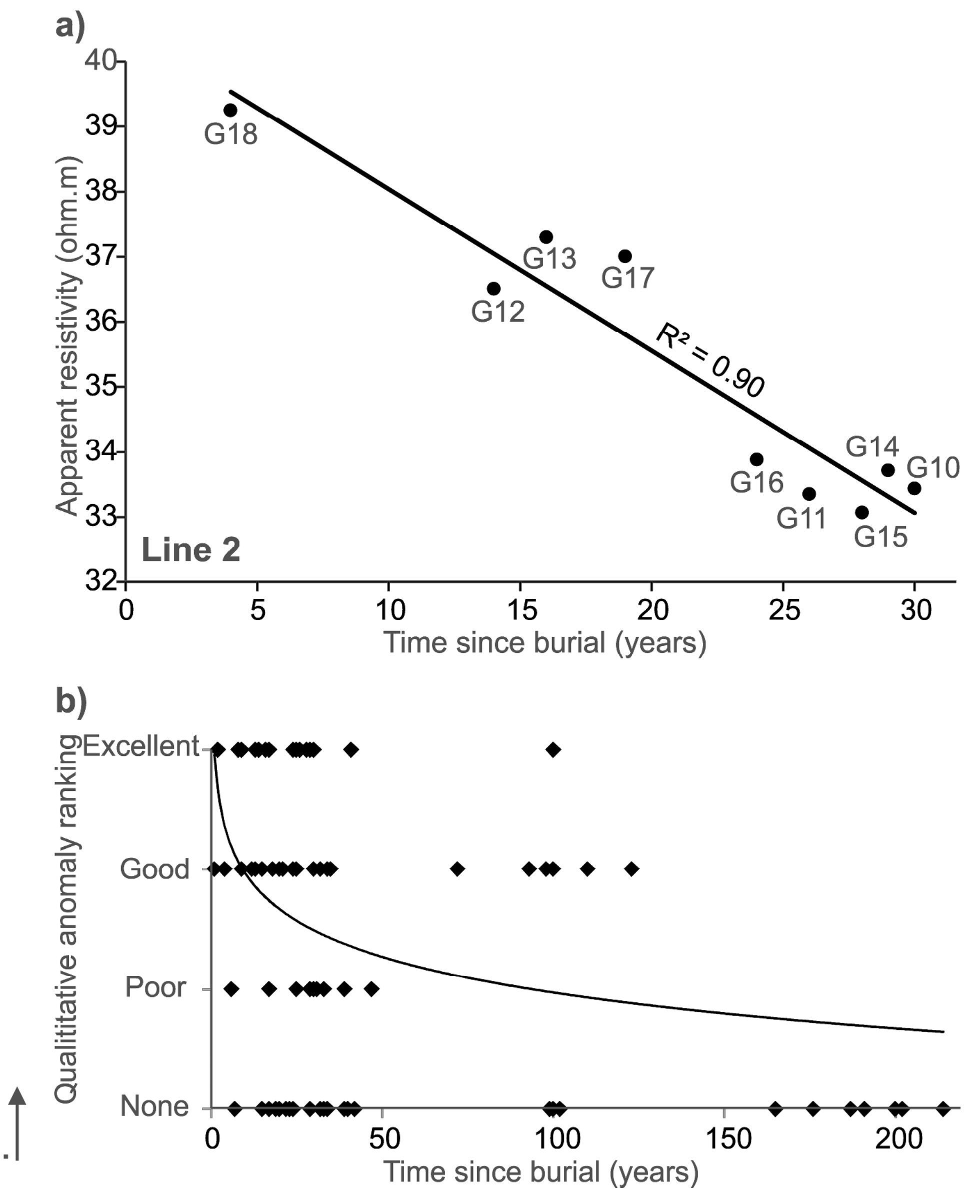


Figure 9. St. Luke's church sandy-pebbly soil graveyard survey line 2 (Fig. 5 for location), Staffordshire, showing grave locations represented by (a) headstones with year of burial inset, (b) magnetic susceptibility and (c) apparent resistivity profile position with marked interpreted burial (Table S3) position.

115x88mm (600 x 600 DPI)



10.

Figure 10. Cross-plots of geophysical responses versus burial age obtained in this study. (a) Survey line 2 (with statistically significant linear trend) of apparent resistivity response versus burial age (Table S1) at St. Michael of All Angels Church clay-rich soil, Stockton, Norfolk, UK. (b) All magnetic susceptibility study qualitative ranking results (see text) versus burial age with general trend, compiled from Tables 3-5.

143x168mm (600 x 600 DPI)

Target(s) Soil type: sand | clay	Cond-uctivity	Resist-ivity	GPR	Mag-netics	Metal detector	Magnetic suscept-ibility
Unmarked grave(s) 0-50 yrs	Medium / Medium	Good / Good	Good / Medium	Medium / Medium	Medium / Medium	Good / Good
Unmarked grave(s) 50-100 yrs	Medium / Medium	Medium / Medium	Good / Medium	Medium / Medium	Poor / Poor	Poor / Poor
Unmarked grave(s) 100+ yrs	Poor / Poor	Poor / Poor	Good / Medium	Poor / Poor	Poor / Poor	Poor / Poor
Clandestine grave(s)	Medium / Medium	Good / Good	Good / Medium	Good / Good	Medium / Medium	Good / Good
Woods	Medium	Poor	Poor	Good	Good	Good
Rural	Good	Good	Good	Good	Good	Good
Urban	Poor	Poor	Medium	Poor	Medium	Poor
Coastal	Poor	Poor	Poor	Good	Good	Good

Table 1. Generalised table to indicate potential of geophysical techniques success for grave(s) location assuming optimum equipment configurations. Note this table does not differentiate between target size, burial depth and other important specific factors (see text). Key: Good; Medium; Poor chances of success. The dominant sand | clay soil end-types are detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types. Modified from Pringle and others (2012a).

Study site	Survey line no.	Apparent Resistivity Min./Av/Max (Ω.m), SD	Magnetic Susceptibility Min./Av/Max (SI x 10^{-6}), SD
St. Michael's Church clay-rich soil, Stockton, Norfolk	1	19.6/23/27, 2 SD	141/267/711, 1 SD
	2	32/38/45.0, 3 SD	36/102/280, 47 SD
	3	18/25/45, 6 SD	83/420/1554, 368 SD
	All	Average: 28 Ω.m	Average: 263 SI
St. Johns Church sandy soil, Keele, Staffs.	1	164/179/194, 5 SD	118/247/700, 128 SD
	2	145/174/227, 22 SD	31/107/206, 399 SD
	3	229/254/284, 17 SD	115/383/1004, 206 SD
	4	219/248/328, 29 SD	35/114/330, 60 SD
	All	Average: 214 Ω.m	Average: 213 SI
St. Luke's Church sandy-pebbly soil, Endon, Staffs	1	116/157/200, 18	159/402/978, 155
	2	117/161/216, 21	131/420/1460, 250
	All	Average: 159 Ω.m	Average: 411 SI

Table 2. Summary statistics (minimum/average/maximum/SD) of respective resistivity and magnetic susceptibility survey line and datasets collected from the three study sites.

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	GPR Antenna central frequency (MHz)		
				225	450	900
G28	2	Excellent	None	None	None	None
G18	4	Good	None	Poor	Poor	Good
G27	12	Good	Good	None	None	None
G26	13	Good	Poor	Poor	None	None
G12	14	Excellent	Excellent	None	Good	Poor
G13	16	Excellent	Poor	None	Poor	Poor
G17	19	None	Poor	None	Poor	Poor
G29	20	Good	Good	None	Poor	Good
G16	24	Excellent	Excellent	None	Poor	Excellent
G11	26	Excellent	Excellent	None	No detection	Poor
G15	28	Excellent	Poor	None	Poor	Poor
G14	29	Excellent	Excellent	None	Poor	Poor
G10	30	Excellent	Excellent	None	Poor	Poor
G19	30	Excellent	Good	Poor	Poor	None
G21	72	Good	None	Poor	Good	Good
G20	98	Good	None	None	Poor	Good
G22	100	None	None	None	Poor	Poor
G23	102	None	None	None	Poor	Poor
G24	110	Good	None	None	Good	Good
G25	123	Good	Good	None	Poor	Good
G4	165	None	None	None	None	Good
G9	176	None	Excellent	Good	Good	Excellent
G8	187	None	None	None	Poor	Poor
G7	191	None	Good	Poor	Good	Excellent
G3	200	None	None	None	None	Good
G6	202	None	None	None	None	None
G5	214	None	Poor	None	None	None
No. of graves detected (29)		17	15	6	19	**21**
No. of graves detected (%)		59%	51%	21%	65%	**72%**

Table 3. Summary of grave detection (ordered in burial age) by geophysical methods at St. Michael's clay-rich soil graveyard, Norfolk, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None (as defined by Schultz and Martin, 2012).

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	GPR Antenna central frequency [MHz]		
				225	**450**	**900**
G12	13	Excellent	None	Good	Good	Good
G15	15	None	Excellent	Poor	No detection	Poor
G14	20	None	Excellent	Poor	Poor	Poor
G4	21	Good	Poor	Good	None	Poor
G19	23	None	Good	Good	Good	Poor
G2	24	Good	Excellent	None	Good	Poor
G7	24	None	Good	None	Good	Excellent
G13	24	None	None	Poor	Poor	Poor
G5	29	Poor	Poor	Poor	Poor	Poor
G1	30	Good	Excellent	None	Poor	Poor
G3	31	Poor	Good	None	Poor	Excellent
G6	32	None	Poor	Poor	Good	Good
G16	33	None	Poor	Poor	Poor	Good
G17	34	None	None	None	None	None
G8	47	Poor	Poor	None	Poor	Poor
G11	93	Good	None	None	Good	Excellent
G18	99	None	None	None	None	None
G9	100	Good	None	None	None	Poor
G10	100	Excellent	Poor	Poor	Poor	Good
No. of graves detected (19)		10	13	10	14	**17**
No. of graves detected (%)		53	68	53	74	**89**

Table 4. Summary of grave detection (ordered in burial age) by geophysical methods at St. John's sandy soil graveyard, Staffordshire, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None (as defined by Schultz and Martin 2012).

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	Antenna central frequency (MHz) 225	450	900
G21	0	None	Good	Poor	None	None
G26	1	Good	Good	Poor	None	None
G38	6	Poor	None	Poor	None	Good
G13	7	None	Excellent	Poor	Good	None
G15	8	Excellent	Excellent	Poor	Poor	Poor
G27	9	Excellent	Excellent	Poor	Poor	Poor
G32	9	Excellent	Good	Poor	None	Poor
G33	9	Excellent	Poor	None	None	Good
G34	9	Good	Good	Poor	Poor	None
G22	14	Excellent	Good	Excellent	Good	None
G6	15	Good	Poor	Good	Poor	Poor
G20	15	None	None	None	None	None
G19	16	Excellent	Poor	Poor	Poor	None
G3	17	Excellent	Excellent	Poor	Poor	None
G8	17	None	Poor	Poor	Poor	Poor
G36	17	Poor	Good	Good	Poor	None
G14	18	Good	Poor	Good	Poor	Poor
G9	20	None	Good	Poor	None	None
G24	24	Excellent	Good	None	Poor	Good
G2	25	Excellent	Poor	Good	Poor	None
G12	25	Excellent	Excellent	Poor	Poor	Poor
G23	25	Poor	Excellent	Poor	Good	Poor
G35	26	Excellent	Good	Good	None	Poor
G30	29	None	Good	None	Poor	Poor
G28	30	Poor	Excellent	Poor	Poor	None
G29	32	Good	Excellent	None	Good	None
G31	32	Good	None	Poor	None	None
G5	33	Poor	Good	Poor	None	Good
G7	34	Good	Excellent	None	Good	None
G16	34	Good	None	Good	None	Poor
G37	35	Good	None	Poor	None	None
G1	39	None	Poor	Poor	None	None
G11	39	Poor	Excellent	None	None	Poor
G10	40	None	None	Poor	Poor	None
G4	41	Excellent	Excellent	Poor	None	None
G17	41	Excellent	None	Poor	None	Poor
G18	42	None	Good	None	None	None
G25	unknown	Good	Excellent	None	None	None
No. of graves detected (38)		29	**31**	29	20	16
No. of graves detected (%)		76	**82**	76	53	42

Table 5. Summary of grave detection (ordered in burial age) by geophysical methods at St. Luke’s sandy-pebbly soil graveyard, Staffs, UK, using the qualitative ranking system of Excellent, Good, Poor and None anomalies (as defined by Schultz and Martin 2012).