GEOPHYSICS®

Determining geophysical responses from graves

Journal:	*Geophysics*
Manuscript ID	GEO-2016-0440
Manuscript Type:	Technical Paper
Date Submitted by the Author:	16-Aug-2016
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Keywords:	case history, ground-penetrating radar (GPR), electrical/resistivity, magnetic susceptibility
Area of Expertise:	Case Histories, Engineering and Environmental Geophysics

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Running Head: Geophysical responses from graves

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Submitted: 16 August 2016

Abstract

Graveyards and cemeteries around the world are being increasingly designated as full. There is a growing requirement to identify burial spaces or to exhume and then re-inter burials if necessary. Near-surface geophysical methods offer a potentially non-invasive target detection solution; however there has been lack of research to identify optimal detection methods using such geophysical techniques. This study has collected multi-frequency (225 MHz – 900 MHz) ground penetrating radar, electrical resistivity and magnetic susceptibility surface data over known burial sites with different burial ages and UK church graveyards. Results indicate that progressively older burials are more difficult to detect but successful grave detection is complicated by soil type. Different geophysical techniques were optimal in the three sites surveyed, which therefore suggests a multi-technique approach should be utilised by survey practitioners. Graveyard geophysical targets included the grave soil present above earth-cut graves, the grave contents themselves, brick-lining (if present) and grave soil leachate plumes that are all geophysically detectable from background levels. Grave markers were also identified as not always being located where the burials were positioned. This study clearly demonstrates the value of these techniques in grave detection and inform search teams detecting clandestine burials.

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

INTRODUCTION

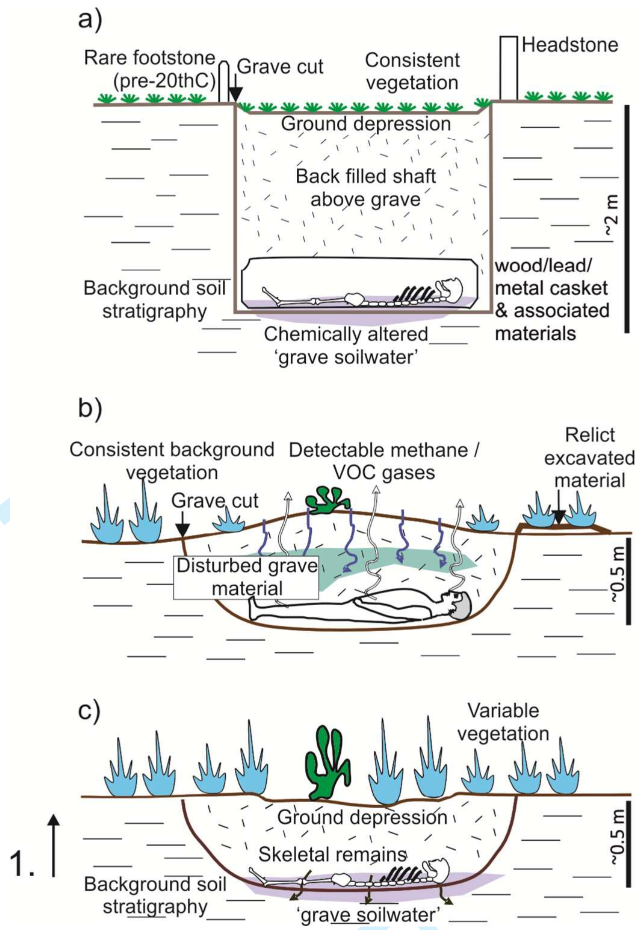
Globally, graveyards and cemeteries are suffering from a severe lack of burial space. With an estimated 55 million individuals dying globally each year (de Sousa, 2015), the problem is most acute in urban areas that do not practise grave recycling. For example, in the UK there are less than 25% of burial grounds that have room to accept new burials (Hansen et al. 2014). Since 1968, when the number of cremations exceeded burials for the first time, cremation has increased considerably. Current figures suggest that around 70% of all funerals are cremations (Coutts et al. 2016). However, the way in which burial space is currently used is not sustainable (see Hussein and Rugg, 2003). The re-use of existing graveyards and cemeteries is one possible solution, for example, burial regulation relaxations have been in force in London since 2005 (Ministry of Justice, 2006). However, burial ground records, if available, rarely indicate burial positions, and even grave headstones, if present, are not always reliable burial position indicators as Fiedler et al. (2009) documents. There have been other studies which document rapidly-dug grave burials for mass fatalities, 19th-century (1845-1851) Irish Potato famine (Ruffell et al. 2009) and early 20th -century (1918-1919) Spanish Flu victims (Davis et al. 2000), evidence depths of burial significantly shallower than the burial ground depths of graves that are commonly 1 m - 1.8 m below ground level (bgl). In order to determine the positions of unmarked burials, probing methods (see Owsley, 1995 for background) would not be deemed appropriate due to religious and social sensitivities, and thus other detection technique(s) need to be considered and optimised for such purposes.

Researchers have used remote sensing methods to identify unmarked burials (e.g. see Brilis et al. 2000a,b). Ruffell et al. (2009) successfully identified historical (150-160 years old) unmarked graves using aerial photographs and confirmed positions by subsequent geophysical surveying. Surface geomorphology methods have also been utilised for successful detection of burial positions (see Ruffell and McKinley, 2014). Localised vegetation growth may also have different characteristics to background areas, for example, different species and with more or stunted growth (Dupras et al. 2006) that Larson et al. (2011) suggests may be due to localised pH soil changes and differing ground characteristics of the burial compared to surrounding areas. Pringle et al. (2012a) reported comprehensive overview of current relevant search methods and case study examples.

A ground-based, non-invasive detection technique that has been utilised to effectively detect graves is near-surface geophysics. Commonly-used methods include electrical resistivity, bulk ground conductivity, magnetic and ground penetrating radar methods (Reynolds, 2011; Pringle et al. 2012a/2016; Gaffney et al. 2015). Electrical resistivity surveys have been successfully used to locate unmarked burials in cemeteries (see, e.g. Matias et al. 2006; Hansen et al. 2014; Buyuksarac et al. 2015). Controlled studies on modern burials evidencing that decompositional fluids may be the dominant factor in graves that is detected electrically (see Jervis et al. 2009; Pringle et al. 2012b), and may be retained in grave soil for considerable periods of time post-burial (see Pringle et al. 2015a). However, it is important to note that the style of formal burials and clandestine graves of murder victims are usually quite different in terms of structure, depth and complexity of the burial contents (Fig. 1). Apart from graveyards and cemeteries being reused, partially excavated, topsoil removed, etc. the graves present can also vary in style from earth-cut (as shown in Fig. 1) to brick-lined, coffined and uncoffined (see Hansen et al. 2014).

It has also been found that local variations in soil type and moisture content, particularly when surveying in dry conditions in heterogeneous ground, affect surveys by masking target locations (see, e.g. Hansen et al. 2014). Electro-magnetic (EM) surveys have shown to have variable detection successes, being affected by above-ground sources (see, e.g. Nobes, 1999; Pringle et al. 2012a). Magnetic surveys for ancient archaeological graves have been successful but for modern burials they have had varied grave detection success (see, e.g. Stanger and Roe 2007; Pringle et al. 2015b). Ground penetrating radar (GPR) has been used to locate unmarked burials in graveyards and cemeteries with varying degrees of success (see, e.g. Nobes, 1999; Fiedler et al. 2009; Hansen et al. 2014; Gaffney et al. 2015), and indeed of a suspected clandestine burial of a murder victim within a graveyard (Ruffell, 2005). Ruffell et al. (2009) suggested mid-range (200 – 400 MHz) frequency antennae for unmarked burials but this varies depending upon specific site factors.

There is, therefore, little information on the optimum geophysical technique(s) for the detection of unmarked graves. This paper aims are *firstly* to detail results of near-surface geophysical investigations of marked graves with known burial dates; *secondly* determine the optimum geophysical detection method(s) and equipment configuration(s) of different aged burials; *thirdly* and finally, to gain knowledge of the effect of different soil types upon grave detection.


a)
Rare footstone
(pre-20thC)
Grave cut
Consistent
vegetation
Headstone
Ground depression
Back filled shaft
above grave
~2 m
Background soil
stratigraphy
wood/lead/
metal casket
& associated
materials
Chemically altered
'grave soilwater'
b)
Consistent background
vegetation
Detectable methane /
VOC gases
Relict
excavated
material
Grave cut
Disturbed grave
material
~0.5 m
c)
Variable
vegetation
Ground depression
Skeletal remains
~0.5 m
1.
Background soil
stratigraphy
'grave soilwater'

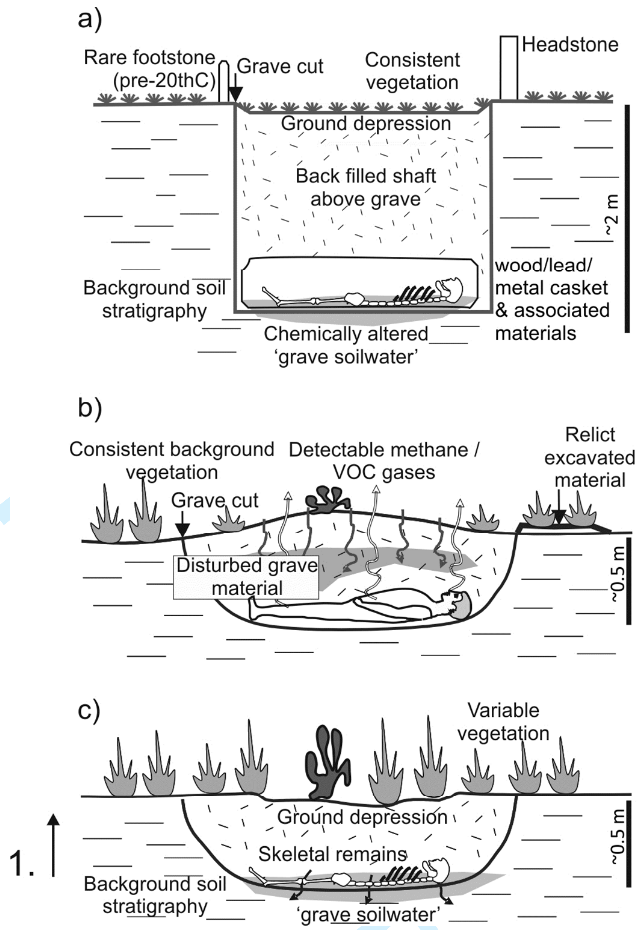
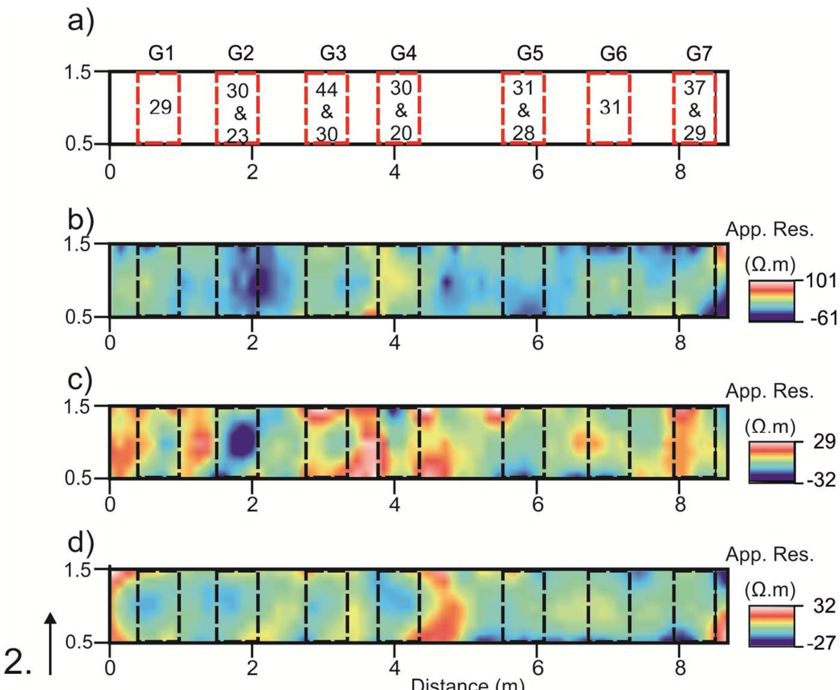


Figure 1. Generalised schematics of (a) isolated graveyard/cemetery burial showing typical geophysical targets including back-fill 'grave' soil, coffin/contents and 'grave fluid', and contrasting with typical clandestine grave with (b) early and (c) late stage decomposition temporal changes (after Pringle et al. 2012). *1 column width*

DATA ACQUISITION

Three study sites were selected within established Church of England graveyards (Figs. S1-S3), as these covered the major sand-clay soil type end members. St. Michael and 'All Angels' Church in Norfolk, UK, had glacial till clay soil overlying Norwich Crag and Cretaceous Chalk bedrock, St. John's Church in Staffordshire, UK, had sandy soil overlying Carboniferous Butterton Sandstone Formation bedrock and St. Luke's Church in Staffordshire, UK had a coarse sandy-pebbly soil overlying Triassic Hawkesmoor Formation sandstones and conglomerate bedrock (see Fig. S4). Each graveyard also had numerous known and accessible grave positions with known contents on headstones and burial ages ranging from the 19th century to the present day (Tables S1-S3). Importantly, these did not have other above-ground grave markers which would have precluded geophysical surveys to be undertaken. Respective parish church councils and their congregations had also given their permission for the study.

Initial trial geophysical surveys were conducted over known burials in all graveyards in order to determine the optimal survey line distance from grave headstones. This was determined to be 0.5m; less than this it may have picked-up the headstone rather than 'grave soil' and further away may it may have missed the grave position (Figs. S5-S6). The optimal electrode probe spacing for electrical resistivity surveys was determined to be also 0.5m spacing (as opposed to 0.25m or 1m) as there were significant variations over the survey area and anomalies could be correlated to burial positions (Fig. 2). It is also recognised that grave markers such as headstones may not be in the correct positions, as previously documented by Fiedler et al. (2009).



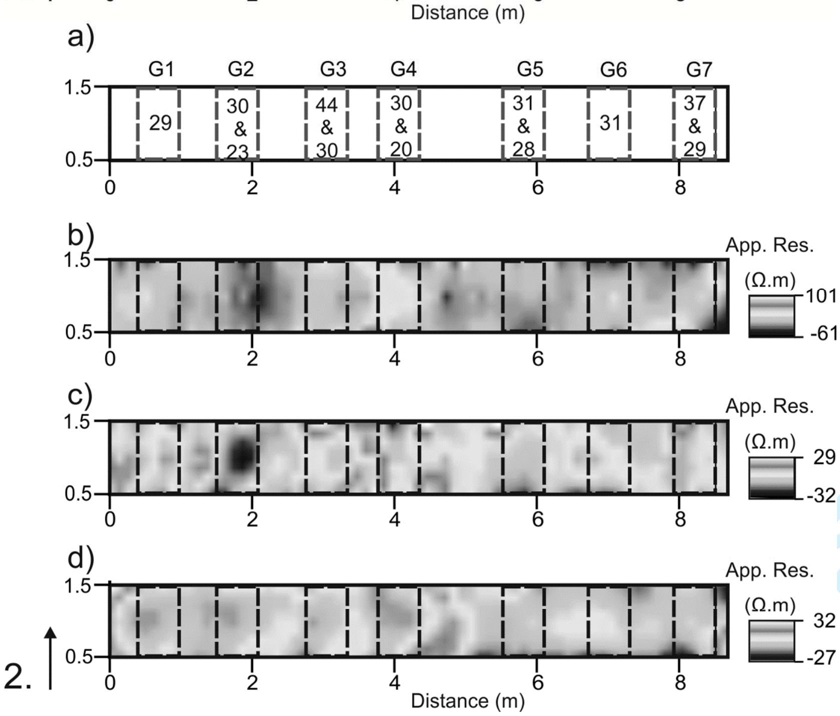


Figure 2. (a) Mapview of graves (with burial ages in years of occupants noted) and subsequent repeat processed electrical resistivity surveys using (b) 0.25 m, (c) 0.5 m and, (d) 1 m separated mobile probes at St. Johns' Church, Staffordshire, UK. - *1.5 column width*

For each full geophysical survey, data acquisition parameters were deliberately maintained for consistency purposes. SensorsandSoftware™ PulseEKKO 100 GPR equipment (Fig. S1) was used to collect 225 MHz, 450 MHz and 900 MHz central frequency fixed-offset antenna datasets at all three study sites. These three frequencies were chosen as they were the most suitable, based on site velocity and attenuation, resolution and penetration depths as others have shown (see, e.g. Pringle et al. 2016; Gaffney et al. 2015; Hansen et al. 2014). Both 110 MHz and 1,200 MHz antenna were inappropriate due to antenna size and trace spacing/penetration depths respectively. Respective GPR data acquisition specifications were: (i) 225 MHz 100 ns time window, 32 stacks and 0.1m 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. A Geoscan™ RM15-D bulk ground electrical resistivity equipment (Fig. S2) with a 0.5 m fixed-offset dipole-dipole electrode probe configuration was used to collect data. The mobile 0.1 m long stainless steel electrodes were separated by 0.5 m, whilst the remote probes were placed ~ 0.75 m apart at a distance ~15 m from the survey position following best practice procedures (see, e.g. Milsom and Eriksen, 2011). Measurements were taken at 0.1 m intervals along all profile lines, with the data logger automatically recorded resistivity measurements at each sampled position. Magnetic susceptibility data was collected using a Bartington™ MS-2D field coil susceptibility meter connected to a laptop using Bartsoft™ v.4 data acquisition software (Fig. S3). A 0.2 m diameter surface probe generates a sample measurement (set at 1 s throughout) when placed on the ground surface at each sampling point to collect data and repeated three times, with a sampling interval of 0.1 m along profile lines. After every 5 sampling points, the probe was raised and aimed upwards 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 each full geophysical survey, data processing was deliberately kept the same for consistency purposes. Standard data processing steps (see, e.g. Cassidy, 2009) were undertaken on the downloaded GPR 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) dewow filter applied, (iv) AGC gain filter, (v) time-cut to clip blank data at base of profiles, (vi) 1D filtering and finally, (vii) time-depth conversion using respective common-mid point (CMP) survey data obtained onsite following standard methodologies (see, e.g. Reynolds, 2011). Standard data processing steps (see, e.g. Milsom and Eriksen, (2011) were also undertaken on the downloaded electrical resistivity and magnetic susceptibility data which were: (i) conversion of measured Resistance (Ω) values to apparent resistivity (Ω.m) to account for probe spacing configuration (ER only); (ii) data de-spiking to remove anomalous data points and; (iii) dataset de-trending to remove long wavelength site trends to allow smaller, grave-sized features to be more easily identified and interpreted (see, e.g. Milsom and Eriksen, 2011). The processed datasets were then graphically plotted to match other techniques for comparison.

RESULTS

Relatively high magnetic susceptibility anomalies and low apparent resistivity anomalies, with respect to background values, could be correlated to known grave positions with additional unknown grave positions located in the clay-rich soil of St. Michael of All Angels' graveyard in Norfolk (Fig. 3). GPR profile results indicated 900 MHz frequency antennae were deemed optimal at this site, for example, detecting the 11 graves on profile 2 (Fig. 4). Other profiles had more variable success at detecting graves at known positions, particularly profile 1 which was nearest the church and had the oldest 19th-century graves (Table S1).

Relative high magnetic susceptibility anomalies and low apparent resistivity anomalies, with respect to background values, could also be correlated to known grave positions with additional unknown grave positions located in the sand-rich soil of St. John's graveyard in Staffordshire (Fig. S7). GPR profile results indicated 450 MHz frequency antennae were deemed optimal at this site, for example, detecting the 11 graves on profile 2 (Fig. 4). Again older graves were more problematic to detect (Table S2), with, interestingly, a double burial (G19) showing remains in the supposed same grave were not positioned vertically (Fig. S8).

3.

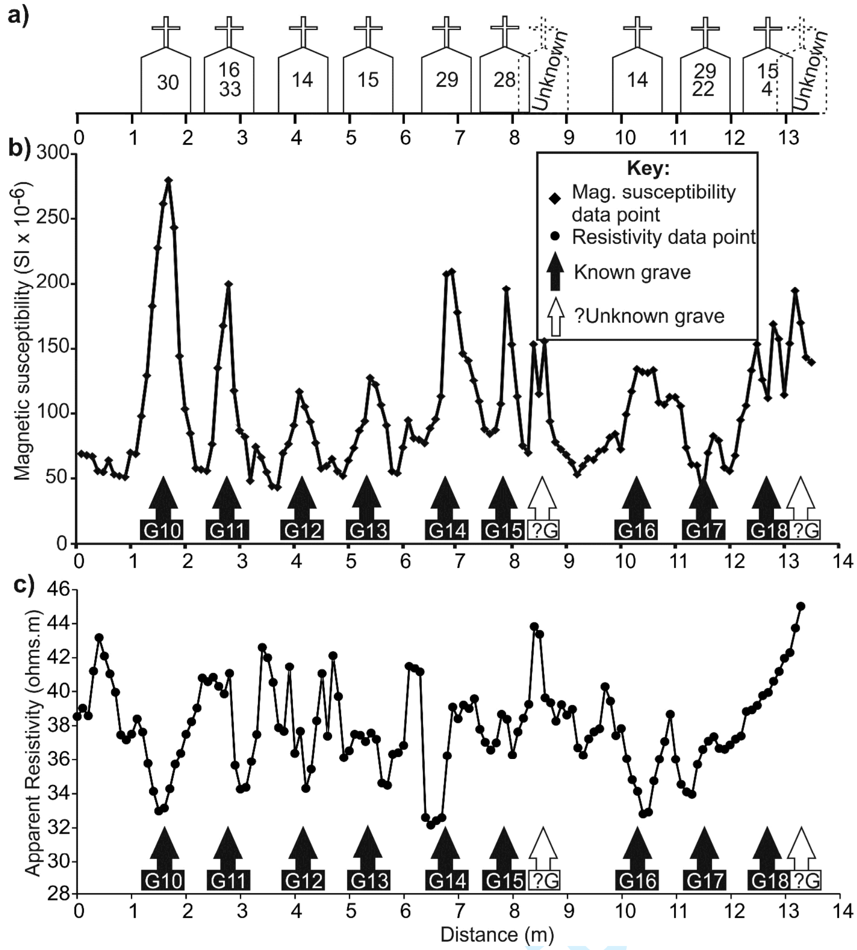


Figure 3. St. Michael's graveyard survey line 2 (Fig. S1 for location), showing (a) grave locations represented by headstones with burial age(s) inset, (b) magnetic susceptibility and (c) apparent resistivity profile, both with numbered (Table 1) grave position anomalies arrowed.

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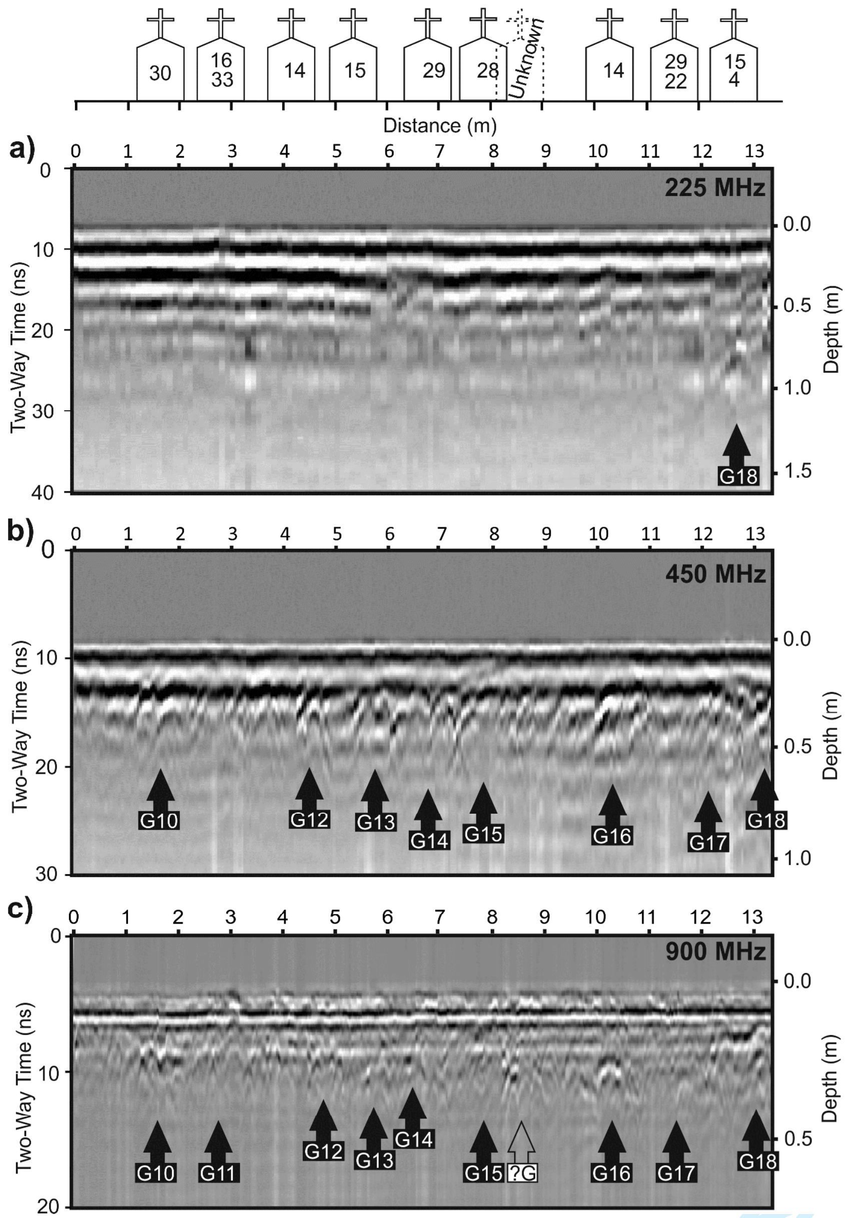

Figure 4. St. Michael's survey line 2 (Fig. S1 for location), showing (a) grave locations represented by headstones with burial age(s) inset, (b) 450 MHz and (c) 900 MHz frequency 2D profiles, both with numbered (Table 1) grave position anomalies arrowed.

- 1.5 column width

Relative low magnetic susceptibility anomalies and low apparent resistivity anomalies, with respect to background values, could be correlated to known grave positions with additional unknown grave positions located in the coarse sand and pebble-rich soil of St. Luke's graveyard in Staffordshire (Fig. S9). GPR profile results here indicated 225 MHz frequency antennae were deemed optimal at this site, for example, detecting 14 out of 20 graves on profile 2 (Fig. S10). Once again, older graves were more problematic to detect (Table S3).

It is difficult to quantify the quality of GPR anomalies that were created over known grave positions. Seismic semblance analysis methods has been used on GPR anomalies (see Booth and Pringle, 2015), but in this real-world dataset the many minor anomalies also present has proven too problematic to conduct this method. Instead a four-fold *Excellent, Good, Poor and None* qualitative grade has been given for all known grave positions in the three graveyards, with the same ranking system for magnetic susceptibility and electrical resistivity datasets respectively (summarised in Tables 1-3 respectively). Other authors have used this method on forensic geophysical datasets (see Schultz, 2008; Pringle et al. 2016). These ranking can then be turned into numerical 0, 1, 2 and 3 respective target detection values and a simple statistical approach used of detected/total number of graves to give a target detection percentage for each site (Tables 1-3 for the three sites respectively).

Tables 1-3. position.

DISCUSSION

The survey results indicate that older graves are progressively more difficult to locate using near-surface geophysical methods, as the measurable geophysical contrast between 'grave targets' (Fig.1) and background levels decreases (Tables S4-S6). This both confirms and extends the results of other shorter-term (6 year) controlled simulated clandestine burial studies (see, for example, Schultz, 2008; Pringle et al. 2016), although, of course, these targets were buried much shallower and without funerary impedimenta such as coffins (see Hansen et al. 2014). This finding would be suspected as one of the main geophysical targets in graveyard surveys, the back-filled 'grave shaft' or cut filled with disturbed soil, would compact over time, reducing both its porosity and moisture content to background undisturbed soil levels, both of which can be detected electrically (see Hansen et al. 2014; Gaffney et al. 2015). Again, controlled studies of shallow simulated clandestine burials over a two-year time period has quantified these changes (see Jervis et al. 2009), but this has now been extended to include targets with burial age averages of 82 years (St. Michael's), 42 years(St. John's) and 23 years (St. Luke's) post-burial respectively (Tables S1-S3 for burial summary statistics). The other major geophysical grave target is the actual interments and their constituents. Human remains undergo fairly rapid decomposition post-burial, typically resulting in skeletonisation, between six months to two years post-burial in UK climates. This would therefore reduce the target size as post-burial time increases, which is particularly important for forensic GPR surveys. Coffins and associated trappings will also degrade and become progressively more difficult to locate (see McGowan and Prangell, 2015). Burial type and style was seen to be a major variable, from earth-cut to brick-lined graves and vaults having significantly different geophysical signatures (Fig. 5 for examples). The resulting leakage and 'leachate plume' is also detectable geophysically by electrical resistivity surveys in the 'grave soil', chiefly due to the leachate conductivity values being much higher than background soil water (see Pringle et al. 2015, control study measurements). This may or may not spread out away from the burial, largely depending upon the soil type. In clay-rich conditions, such as those at St. Michael's, the leachate plume will be largely retained within the grave soil, whereas in more sandy soils, the leachate will spread much further and predominantly by gravitational processes; this is actually beneficial as it will create a larger target area to be geophysically detected (Fig. S7). An additional complication is that conductivity values of leachate plume, compared to background 'soil water', is also temporally variable, with controlled studies evidencing a relatively rapid increase in conductivity to a maximum after two years of burial, before then reducing to background soil water values after five years of burial (see Pringle et al. 2015a).

As the burial ages in the geophysical targets in this study are *importantly* known (Tables S1-S3), cross-plots can be generated to determine the geophysical response of graves versus their burial ages. For relatively recent graveyard burials, there was an observed statistically significant declining linear correlation between burial age and electrical resistivity response for St. Michael's burials (Fig. 6a), but there were significant variations observed between the three study sites shown here (Fig. 6b), and even within the same study sites, particularly within St. Michael's graveyard which has large resistivity and magnetic susceptibility measurement variations (Fig.3). Therefore, even when looking at similarly-aged graveyard burials and using the same equipment and configurations, respective datasets show significant variations in target detectability (Tables 1-3); soil type was the major variable in the geophysical detection of grave targets.

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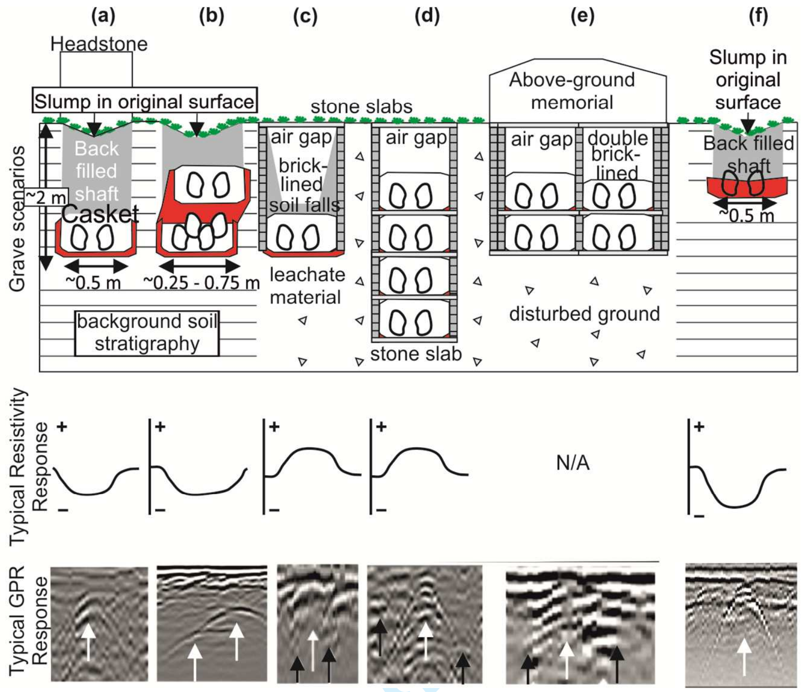

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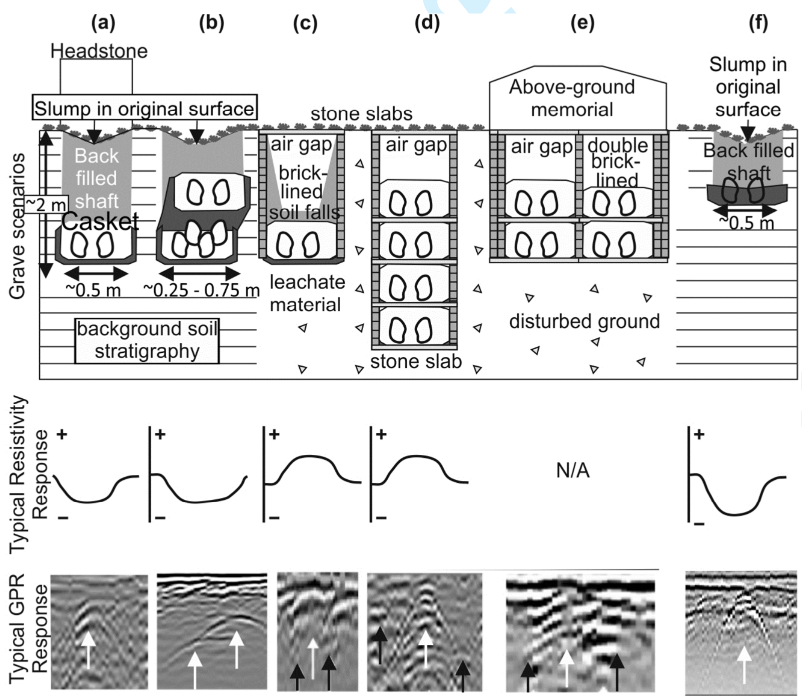
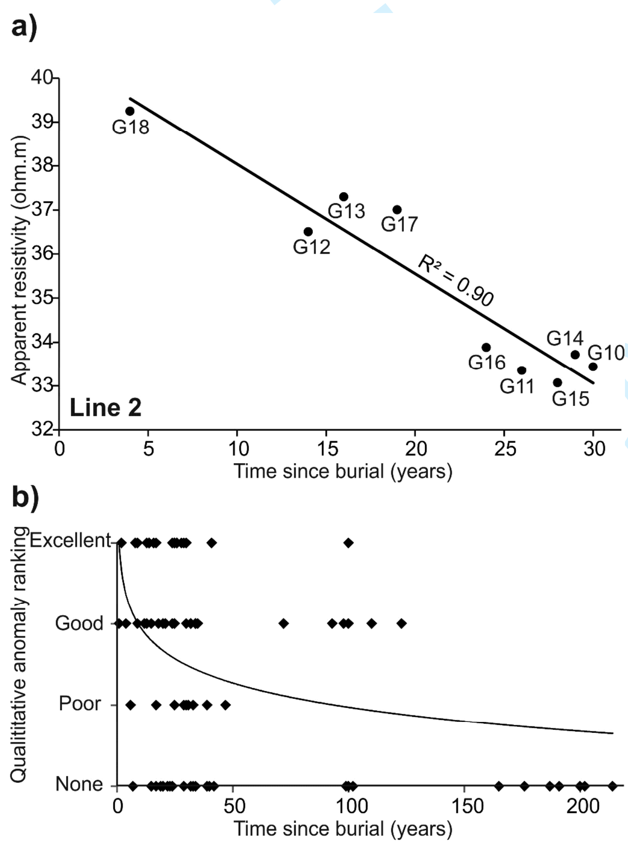


Figure 5. (top) Generalised schematic of burial styles encountered in graveyards and cemeteries with typical (middle) electrical resistivity and (bottom) GPR 2D profile anomalies (white arrows) showing (left to right): (a) isolated earth-cut grave with common wooden (or

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. After Hansen et al. (2014).

The optimum geophysical detection method(s) and equipment configuration(s) to detect burials varied between study sites when accounting for burial ages. By using the results shown in Tables 1-3, numerical values of 3-0 can be assigned to the *Excellent*, *Good*, *Poor* and *None* anomaly detectability ratings (see Schultz, 2008 for background) and a simple statistical ratio approach can be applied (total detected/total graves) to give a target percentage for the three study sites (Tables 1-3). For each study site a different technique proved most effective and, as such, a multi-technique approach is recommended for geophysical surveys of graveyards. This is an important finding due to the popularity of GPR surveys over all other techniques (see, e.g. Pringle et al. 2012), something for search practitioners to consider when designing surveys. Firstly, when considering the magnetic susceptibility surveys themselves, grave locations were detected as relatively high magnetic susceptibility anomalies compared to background values and with target detection rates of 53% for clay-rich soils and 33% for the sandy soils, except for the coarse sand/pebbly soil study where they were seen as relatively low anomalies compared to background values with a target detection rate of 56%. Secondly, for the electrical resistivity surveys that found 0.5m probe spacing to be optimal, nearly all graves that were detected were relatively low resistance compared to background values, but target detection varied widely from 41% for clay-rich and 39% for sand-rich soils to 58% for the coarse sand/pebbly soils respectively. Lastly, the GPR geophysical surveys, 900 MHz frequency antenna was deemed optimal in both the clay-rich soil of St. Michael's graveyard and the sandier soil of St. John's graveyard study sites for target detection (both studies detecting 43% of targets - Tables S1-S2), in contrast to the optimal 225 MHz frequency antenna in the coarse sand and pebbly-soil of St. Luke's graveyard (detecting 32% of targets - Table S3). Clearly smaller trace spacings used for higher frequency antenna will improve target resolution as more data is collected over each target grave, but this will increase survey time. Table 4 provides a graphical summary of the major study outcomes.



6.

Figure 6. (a) Survey line 2 cross-plot of apparent resistivity response against burial age (Table S1) at St. Michael of All Angels, Norfolk, UK. (b) All magnetic susceptibility study results cross-plot of detection rating against burial age (Tables S4-S6). – *1 column width*

CONCLUSIONS

Selected known grave positions and burial ages in three Anglican graveyards, with varying soil types, were geophysically surveyed using multi-frequency GPR, electrical resistivity and surface magnetic susceptibility techniques. Whilst target detection did decrease as burial age increased as expected, the results here showed that soil type was a major variable. Instead of one geophysical technique being optimal for overall target detection, all three techniques were optimal in clay-rich (magnetic susceptibility), sandy (electrical resistivity) and coarse sand and pebbly (225 MHz GPR) soil types respectively when looking at geophysical anomaly quality. Relatively high frequency antenna (900 MHz) was optimal in two out of the three graveyards surveyed, with 0.5m spaced electrode probes found to be optimal for electrical resistivity surveys.

The results of this study also show that known grave marker positions may not be accurate. Clearly increasing the numbers of surveyed graves in the dataset would provide more confidence of the study results with burial age spread from 200 years to the present day but this was not possible with the graveyards in this study due to the burial ages and above-ground materials present. More graveyards with different soil types would also prove beneficial to survey to validate and improve these study results, for example, peat-rich soils, saline coastal soils, etc. Obviously other burial grounds in different climates and depositional environments would also be helpful to survey and compare to these data sets. It would also prove beneficial to survey burials from other religious faiths, or indeed so-called green burials to see what effect different burial styles have on target detection. The datasets and technique development for these complex environments where there are known grave contents add value to the investigations being conducted for clandestine burials.

ACKNOWLEDGEMENTS

Henry Dick is supported by the Nigerian Tertiary Education Fund. Daniel Roberts (Keele University) and Matteo Giubertoni (Polimi University) are thanked for initial data collection. The Reverends Peter Jones of St. John's Church, Keele, Staffordshire, UK, Alan Betts of St. Luke's, Endon, Staffordshire, UK, and Julie Oddy-Bates of St. Michael and All Angels', Stockton, Norfolk, UK, and their congregations are thanked for respective site access and for allowing this project to be conducted. This project has passed Keele University's ethical review panel. Supporting datasets are available within the online Supplementary files.

REFERENCES

Coutts, C. C. Basmajian, and T. Chapin, 2016, Projecting landscapes of death: Landscape Urban Planning, **102**, 254-261. doi:10.1016/j.landurbplan.2011.05.005

Booth, A., and J.K. Pringle, 2016, Semblance analysis to assess GPR data from a five-year study of simulated clandestine graves: Journal of Applied Geophysics, **125**, 37-44. doi:10.1016/j.jappgeo.2015.11.016

Brilis, G.M., C.L. Gerlach, and R.J. van Waasbergen, 2000a, Remote sensing tools assist in environmental forensics, Part I: traditional methods: Environmental Forensics, **1**, 63–67. doi:10.1006/enfo.2000.0009

Brilis, G.M., R.J. van Waasbergen, P.M. Stokely, and C.L. Gerlach, 2000b, Remote sensing tools assist in environmental forensics, Part II digital tools: Environmental Forensics, **1**, 1–7. doi:10.1006/enfo.2000.0033

Buyuksarac, A.B. C.C. Yalciner, Y.L. Ekinci, A. Demirci, and M.A. Yucel, 2015, Geophysical investigations at Agadere Cemetery, Gallipolli Peninsular, NW Turkey: Australian Journal of Forensic Sciences, **46**, 111-123. doi:10.1080/00450618.2013.804948

Cassidy, N.J., 2009, Ground penetrating radar data processing, modelling and analysis, *in* H.M. Jol, eds., Ground Penetrating Radar: Theory and Applications, Elsevier. ISBN: 978-0-444-53348-7

Davis, J.L., J.A. Heginbottom, A.P. Annan, R.S. Daniels, B.P. Berdal, et al., 2000, Ground penetrating radar surveys to locate 1918 Spanish flu victims in permafrost; Journal of Forensic Sciences, **45**, 68–76. doi:10.1520/JFS14642J

De Sousa, A.N., 2015, Death in the city: what happens when all our cemeteries are full? accessed 9 June 2016; https://www.theguardian.com/cities/2015/jan/21/death-in-the-city-what-happens-cemeteries-full-cost-dying.

Dupras, T.L. J.J. Schultz, S.M. Wheeler, and L.J. Williams, 2006, Forensic recovery of human remains: CRC Press. ISBN: 0849329825.

Fiedler, S., J. Breur, C.M. Pusch, S. Holley, J. Wahl, J. Ingwersen, and M. Graw, 2012, Graveyards – special landfills: Science of the Total Environment, **419**, 90-97. doi: 10.1016/j.scitotenv.2011.12.007

Fiedler, S., B. Illich, J. Berger, and M. Graw, 2009, The effectiveness of ground-penetrating radar surveys in the location of unmarked burial sites in modern cemeteries: Journal of Applied Geophysics, **68**, 380–385. doi:10.1016/j.jappgeo.2009.03.003

Gaffney, C., C. Harris, F. Pope-Carter, J. Bonsall, R. Fry, and A. Parkyn, 2015, Still searching for graves: an analytical strategy for interpreting geophysical data used in the search for “unmarked” graves: Near Surface Geophysics, **13**, 557-569. doi:10.3997/1873-0604.2015029

Hansen, J.D., J.K. Pringle, and J. Goodwin, 2014, GPR and bulk ground resistivity surveys in graveyards: locating unmarked burials in contrasting soil types: Forensic Science International, **237**, e14-e29. doi:10.1016/j.forsciint.2014.01.009

Hussein, I., and J. Rugg, 2003, Managing London’s dead: a case of strategic policy failure: Mortality, **8**, 209-221. doi: 10.1080/1357627031000087433

Jervis, J.R., and J.K. Pringle, 2014, A study of the affect of seasonal climatic factors on the electrical resistivity response of three experimental graves: Journal of Applied Geophysics, **108**, 53-60. doi:10.1016/j.jappgeo.2014.06.008

Jervis, J.R., J.K. Pringle, and G.T. Tuckwell, 2009, Time-lapse resistivity surveys over simulated clandestine burials: Forensic Science International, **192**, 7-13. doi:10.1016/j.forsciint.2009.07.001

Larson, D.O., A.A. Vass, and M. Wise, 2011, Advanced scientific methods and procedures in the forensic investigation of clandestine graves: Journal of Contemporary Criminal Justice, **27**, 149–182. doi:10.1177/1043986211405885

Matias, H.C., F.A. Monteiro Santos, F.E. Rodruiges Ferreira, C. Machado, and R. Luzio, 2006, Detection of graves using the micro-resistivity method: Annals of Geophysics, **49**, 1235–1244. doi:10.4401/ag-3102

McGowan, G., and J. Prangnell, 2015, A method for calculating soil pressure overlying human burials: Journal of Archaeological Sciences, **53**, 12-18. doi:10.1016/j.jas.2014.09.016

Milsom, J., and A. Eriksen, 2011, Field Geophysics, 4th ed: Wiley. ISBN: 978-0-470-74984-5

Ministry of Justice, Burial Law and Policy in the 21st Century: The Need for a Sensitive and Sustainable Approach, 2006. accessed 18 November 2015; www.gov.uk/government/uploads/system/uploads/attachment_data/file/162865/burial_grounds_web_whole_plus_bookmarks.pdf.

Nobes, D.C., 1999, Geophysical surveys of burial sites: a case study of the Oaro Urupa site: Geophysics, **64**, 357–367. doi:10.1190/1.1444540

Owsley, D.W., 1995, Techniques for locating burials, with emphasis on the probe: Journal of Forensic Sciences, **40**, 735–740. doi:10.1520/JFS15375J

Pringle, J.K., J.R. Jervis, D. Roberts, H.C. Dick, K.D. Wisniewski, et al., 2016, Geophysical monitoring of simulated clandestine graves using electrical and ground penetrating radar methods: 4-6 years: Journal of Forensic Sciences, **61**, 309-321. doi: 10.1111/1556-4029.13009

Pringle, J.K., J.P. Cassella, J.R. Jervis, A. Williams, P. Cross, et al. 2015a, Soilwater conductivity analysis to date and locate clandestine graves of homicide victims: Journal of Forensic Sciences, **60**, 1052-1060. doi:10.1111/1556-4029.12802

Pringle, J.K, K.D. Wisniewski, M. Giubertoni, N.J. Cassidy, J.D. Hansen, et al., 2015b, The use of magnetic susceptibility as a forensic search tool: Forensic Science International, **246**, 31-42. doi:10.1016/j.forsciint.2014.10.046

Pringle, J.K., A. Ruffell, J.R. Jervis, L. Donnelly, J. McKinley, et al., 2012a, The use of geoscience methods for terrestrial forensic searches: Earth Science Reviews, **114**, 108-123. doi:10.1016/j.earscirev.2012.05.006

Pringle, J.K., J.R. Jervis, J.D. Hansen, N.J. Cassidy, G.M. Jones, et al, 2012b, Geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 0-3 years: Journal of Forensic Sciences, **57**, 1467-1486. doi: 10.1111/j.1556-4029.2012.02151.x

Reynolds, J.M., 2011, An introduction to applied and environmental geophysics. 2nd ed: Wiley. ISBN: 9780471485360.

Ruffell, A., and J. McKinley, 2014, Forensic geomorphology: Geomorphology*,* **206**, 14-22. doi:10.1016/j.geomorph.2013.12.020

Ruffell, A., J.K. Pringle, and S. Forbes, 2014, Search protocols for hidden forensic objects beneath floors and within walls: Forensic Science International, **237**, 137-145. doi:10.1016/j.forsciint.2013.12.036

Ruffell, A., A. McCabe, C. Donnelly, and A. Sloan, 2009, Location and assessment of an historic (150–160 years old) mass grave using geographic and ground penetrating radar investigation, NW Ireland: Journal of Forensic Sciences, **54**, 382–394. doi: 10.1111/j.1556-4029.2008.00978.x

A. Ruffell, 2005, Searching for the IRA “disappeared”: ground penetrating radar investigation of a churchyard burial site: Journal of Forensic Sciences, **50**, 1430-1435. doi:10.1520/JFS2004156

Schultz, J.J., 2008, Sequential monitoring of burials containing small pig cadavers using ground-penetrating radar: Journal of Forensic Sciences, **53**, 279–287. doi:10.1111/j.1556-4029.2008.00665.x

Stanger, R., and D. Roe, 2007, Geophysical surveys at the West End Cemetery, Townsville: an application of three techniques: Australian Archaeology, **65**, 44–50.

FIGURE CAPTIONS:

Figure 1. Generalised schematics of (a) isolated graveyard/cemetery burial showing typical geophysical targets including back-fill 'grave' soil, coffin/contents and 'grave fluid' and, (b) typical clandestine grave with early and late stage decomposition temporal changes (after Pringle et al. 2012).

Figure 2. (a) Mapview of graves (with burial ages in years of occupants noted) and subsequent repeat processed electrical resistivity surveys using (b) 0.25 m, (c) 0.5 m and, (d) 1 m separated mobile probes at St. Johns' Church, Staffordshire, UK.

Figure 3. St. Michael's graveyard survey line 2 (Fig. S1 for location), showing (a) grave locations represented by headstones with year of burial inset, (b) magnetic susceptibility and (c) apparent resistivity profile (with grave positions arrowed) all on common distance scale.

Figure 4. St. Michael's survey line 2 (Fig. S1 for location), showing (a) grave locations represented by headstones with year of burial (inset) with anomalies (arrowed) all on common distance scale.

Figure 5. (top) Generalised schematic of burial styles encountered in graveyards and cemeteries with typical (middle) electrical resistivity and (bottom) GPR 2D profile anomalies (white arrows) showing (left to right): (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. After Hansen et al. (2014).

Figure 6. (a) St. Michael of All Angels, Norfolk, UK, survey line 2 cross-plot of apparent resistivity response against burial age (Table S1). (b) All magnetic susceptibility study results cross-plot of detection rating against burial age (Tables S4-S6).

TABLE CAPTIONS:

Table 1. Summary of grave (see Table S1) detection by geophysical methods at St. Michael's graveyard, Norfolk, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None, as defined by other authors (see Pringle et al. 2016).

Table 2. Summary of grave (see Table S2) detection by geophysical methods at St. John's graveyard, Staffordshire, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None as defined by other authors (see Pringle et al. 2016).

Table 3. Summary of grave (see Table S2) detection by geophysical methods at St. Luke's graveyard, Staffordshire, UK, using a qualitative ranking system of Excellent, Good, Poor and None anomalies as defined by other authors (see Pringle et al. 2016).

Table 4. 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/age 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 (2012).

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	GPR Antenna central frequency (MHz)		
				225	450	900
G3	200	None	None	None	None	Good
G4	165	None	None	None	None	Good
G5	214	None	Poor	None	None	None
G6	202	None	None	None	None	None
G7	191	None	Good	Poor	Good	Excellent
G8	187	None	None	None	Poor	Poor
G9	176	None	Excellent	Good	Good	Excellent
G10	30	Excellent	Excellent	None	Poor	Poor
G11	26	Excellent	Excellent	None	No detection	Poor
G12	14	Excellent	Excellent	None	Good	Poor
G13	16	Excellent	Poor	None	Poor	Poor
G14	29	Excellent	Excellent	None	Poor	Poor
G15	28	Excellent	Poor	None	Poor	Poor
G16	24	Excellent	Excellent	None	Poor	Excellent
G17	19	None	Poor	None	Poor	Poor
G18	4	Good	None	Poor	Poor	Good
G19	30	Excellent	Good	Poor	Poor	None
G20	98	Good	None	None	Poor	Good
G21	72	Good	None	Poor	Good	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
G26	13	Good	Poor	Poor	None	None
G27	12	Good	Good	None	None	None
G28	2	Excellent	None	None	None	None
G29	20	Good	Good	None	Poor	Good
Maximum detection strength (%)		**53%**	41%	9%	28%	43%

Table 1. Summary of grave (see Table S1) detection by geophysical methods at St. Michael's graveyard, Norfolk, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None, as defined by other authors (see Pringle et al. 2016).

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	GPR Antenna central frequency [MHz] 225	450	900
G1	30	Good	Excellent	None	Poor	Poor
G2	24	Good	Excellent	None	Good	Poor
G3	31	Poor	Good	None	Poor	Excellent
G4	21	Good	Poor	Good	None	Poor
G5	29	Poor	Poor	Poor	Poor	Poor
G6	32	None	Poor	Poor	Good	Good
G7	24	None	Good	None	Good	Excellent
G8	47	Poor	Poor	None	Poor	Poor
G9	100	Good	None	None	None	Poor
G10	100	Excellent	Poor	Poor	Poor	Good
G11	93	Good	None	None	Good	Excellent
G12	13	Excellent	None	Good	Good	Good
G13	24	None	None	Poor	Poor	Poor
G14	20	None	Excellent	Poor	Poor	Poor
G15	15	None	Excellent	Poor	No detection	Poor
G16	33	None	Poor	Poor	Poor	Good
G17	34	None	None	None	None	None
G18	99	None	None	None	None	None
G19	23	None	Good	Good	Good	Poor
Max. detection strength (%)		33%	39%	9%	28%	**43%**

Table 2. Summary of grave (see Table S2) detection by geophysical methods at St. John's graveyard, Staffordshire, UK, using a qualitative anomaly ranking system of Excellent, Good, Poor and None as defined by other authors (see Pringle et al. 2016).

Grave no.	Burial age (yrs)	Magnetic. Suscept.	App. Resistivity	Antenna central frequency (MHz) 225	450	900
G1	39	None	Poor	Poor	None	None
G2	25	Excellent	Poor	Good	Poor	None
G3	17	Excellent	Excellent	Poor	Poor	None
G4	41	Excellent	Excellent	Poor	None	None
G5	33	Poor	Good	Poor	None	Good
G6	15	Good	Poor	Good	Poor	Poor
G7	34	Good	Excellent	None	Good	None
G8	17	None	Poor	Poor	Poor	Poor
G9	20	None	Good	Poor	None	None
G10	40	None	None	Poor	Poor	None
G11	39	Poor	Excellent	None	None	Poor
G12	25	Excellent	Excellent	Poor	Poor	Poor
G13	7	None	Excellent	Poor	Good	None
G14	18	Good	Poor	Good	Poor	Poor
G15	8	Excellent	Excellent	Poor	Poor	Poor
G16	34	Good	None	Good	None	Poor
G17	41	Excellent	None	Poor	None	Poor
G18	42	None	Good	None	None	None
G19	16	Excellent	Poor	Poor	Poor	None
G20	15	None	None	None	None	None
G21	22	None	Good	Poor	None	None
G22	14	Excellent	Good	Excellent	Good	None
G23	25	Poor	Excellent	Poor	Good	Poor
G24	24	Excellent	Good	None	Poor	Good
G25	unknown	Good	Excellent	None	None	None
G26	1	Good	Good	Poor	None	None
G27	9	Excellent	Excellent	Poor	Poor	Poor
G28	30	Poor	Excellent	Poor	Poor	None
G29	32	Good	Excellent	None	Good	None
G30	29	None	Good	None	Poor	Poor
G31	32	Good	None	Poor	None	None
G32	9	Excellent	Good	Poor	None	Poor
G33	9	Excellent	Poor	None	None	Good
G34	9	Good	Good	Poor	Poor	None
G35	26	Excellent	Good	Good	None	Poor
G36	17	Poor	Good	Good	Poor	None
G37	35	Good	None	Poor	None	None
G38	6	Poor	None	Poor	None	Good
Max. detection strength (%)		56%	**58%**	32%	22%	18%

Table 3. Summary of grave (see Table S2) detection by geophysical methods at St. Luke's graveyard, Staffordshire, UK, using a qualitative ranking system of Excellent, Good, Poor and None anomalies as defined by other authors (see Pringle et al. 2016).

Target(s)	**Near-Surface Geophysics**						
Soil type: sand ○|○ clay	Seis-mology /	Cond-uctivity	Resist-ivity	GPR	Mag-netics	Metal detector	Magnetic suscept-ibility
Unmarked grave(s) 0-50 yrs	○|○	◍|◍	●|●	●|◍	◍|◍	◍|◍	●|●
Unmarked grave(s) 50-100 yrs	○|○	◍|◍	◍|◍	●|◍	◍|◍	○|○	○|○
Unmarked grave(s) 100+ yrs	○|○	○|○	○|○	●|◍	○|○	○|○	○|○
Clandestine grave(s)	○|○	◍|◍	●|●	●|◍	●|●	◍|◍	●|●
Common depositional environment							
Woods	○|○	◍	○	○	●	●	●
Rural	○|○	●	●	●	●	●	●
Urban	○|○	○	○	◍	○	◍	○
Coastal	○|○	○	○	○	●	●	●

Table 4. 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/age 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 (2012).