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Long-term geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 4-6 years after burial

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ABSTRACT

This ongoing monitoring study provides forensic search teams with systematic geophysical data over simulated clandestine graves for comparison to active cases. Simulated ‘wrapped’, ‘naked’ and ‘control’ burials were created. Multiple geophysical surveys were collected over six-years, here showing data from four to six years after burial. Electrical resistivity (twin electrode and ERI), multi-frequency GPR, grave and background soilwater were collected. Resistivity surveys revealed the naked burial had low-resistivity anomalies up to year four but then difficult to image, whereas the wrapped burial had consistent large high-resistivity anomalies. GPR 110-900 MHz frequency surveys showed the wrapped burial could be detected throughout, but the naked burial was either not detectable or poorly resolved. 225 MHz frequency GPR data were optimal. Soil water analyses showed decreasing (year four-five) to background (year six) conductivity values. Results suggest both resistivity and GPR surveying if burial style unknown, with winter to spring surveys optimal and increasingly important as time increases.

Keywords: forensic science; forensic geophysics; clandestine grave; monitoring; electrical resistivity; ground penetrating radar; conductivity

Forensic search methods vary widely, for example, in the UK a search strategist is usually involved in a case at an early stage to decide upon the highest probability of search success [1], whereas in other countries a search may not be methodical, investigations may not be standardised and a variety of techniques are undertaken, depending upon local experience [2]. Metal detector search teams [3-5] and specially trained search dogs [5-7] are both commonly used during either initial investigations or as part of a phased sequential programme.

Forensic investigators have been increasingly using geoscientific methods to aid in civil or criminal forensic investigations, predominantly to assist search teams or for trace evidence purposes [8-11]. One key and high-profile 'target' for forensic search teams to detect and locate is human remains buried within clandestine graves [1,5,12]. These searches generally start from large-scale remote sensing methods [13-14], aerial and ultraviolet photography [10,15], thermal imaging [16], to ground-based observations of vegetation changes [4], surface geomorphology changes [17], soil type [1] and depositional environment(s) [10], near-surface geophysics [11], diggability surveys [1] and probing of anomalous areas [18,19] before topsoil removal [4], and finally controlled excavation and recovery [5,15,20]. A typical search will only use a few of these techniques, depending on the circumstances of each case (Colin Hope, *pers. comm.*).

Near-surface geophysical methods rely on there being a detectable physical contrast between the target and the background (or host) materials (see [21]). Near-surface geophysical surveys have been used to try and locate clandestine graves in a number of reported criminal search investigations [3,5,22-32]. Geophysical surveys collected over simulated burials have been undertaken in order to collect control data (e.g. [33-37]. These studies have shown that the resulting geophysical responses could be well predicted, although responses seem to vary both temporally after burial and between different study sites. A few studies have also collected repeat (time-lapse) geophysical surveys over controlled experiments (e.g. [26,38-44]), which have documented temporal changes in geophysical responses over their study periods. However, uncertainties still remain over what and how long temporal variations occur in geophysical surveys after burial, with study survey sites needing to be fully characterised (e.g. geologically and climatologically) to allow comparisons with other studies or indeed for active forensic cases. Documenting temporal changes is important as geophysical responses from recent clandestine burials are known to vary more than archaeological graves. Potential reasons for this could be the temporal changes in grave soil characteristics, decomposition products [45], climatic variations, soil moisture content [46] and other site specific factors (see [11]).

This study continued the systematic assessment of the changing geophysical response of simulated clandestine graves during four to six years after burial. Geophysical survey results from zero to three years after burial were published in [47]. A clandestine grave was defined in this study as an unrecorded burial that has been hand-excavated and dug <1 m depth below ground level (bgl). It should be noted that geophysical results will vary depending upon the depth of burial and indeed on local soil type as [11] reviews. The discovered graves published in [15,48] were usually rectangular in plan-view, mostly hurriedly hand dug using garden implements and usually just large enough to deposit the victim before being back-filled with excavated soil and associated surface debris. [48] also detailed that almost half of the 87 documented U.S. cases were either clothed or encased in material (plastic or fabric), so the authors decided to use two end member scenarios for this study; namely one burial containing a *naked* cadaver and another containing a cadaver *wrapped* in a tarpaulin. It is, however, emphasised that these obviously do not represent all types of potential style of burial with [42] considering other scenarios.

There are many potential near-surface geophysical search techniques that could be utilised to search for clandestine graves that the [47] monitoring paper summarises; this ongoing study has concentrated on collecting electrical resistivity (fixed-offset and Electrical Resistivity Imaging 2D profiles) and Ground Penetrating Radar (110 – 900 MHz frequency 2D profiles. Resistivity surveys showed consistent low anomalies, compared to background values, for a naked burial, in contrast with the wrapped burial which had smaller and varied low/high anomalies and was thus harder to locate [47]. Analyses of decompositional fluids showed highest conductivity values, compared to background soilwater, was ~1 year to ~2 years after burial before subsequently decreasing [47]. GPR surveys finally showed low frequency antennae were consistently optimal for target detection [47].

The aims of this continued four to six year geophysical monitoring study of different simulated burial style clandestine burials were to answer some basic questions posed by forensic search teams. Appropriate site data (rainfall, temperature, soil and 'grave' water conductivities) were also continued to be simultaneously collected in order to allow comparisons with other research studies and criminal search investigations. Basic forensic search questions which were continued to be addressed by this study were:

A) Could twin electrode (fixed-offset) and electrical resistivity imaging surveys still successfully locate both simulated clandestine burials beyond three years after burial? And if so, how long were they geophysically detectable for?

B) Could single profile GPR surveys successfully locate both simulated clandestine burials throughout the four to six year post-burial monitoring period? If this was the case, which dominant frequency antenna was optimal to detect them?

C) When was the optimal time (both up to six years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey?

D) ***W***hen should a forensic geophysical survey be undertaken in a six year search scenario?

Methodology

Study site

The chosen controlled test site was located on Keele University campus, ~ 200 m above sea level, close to the town of Newcastle-under-Lyme in Staffordshire, UK. The local climate is temperate, which is typical for the UK [49]. The study site was a grassed, small rectangular area (~25 m x ~25 m), surrounded by small deciduous trees (Fig. 1). The geophysical survey area measured 5 m x 14 m and sloped by approximately 3º from northwest to southeast. Within this area were the 'naked pig' grave, the empty grave and the 'wrapped pig' grave emplaced in sandy loam soil (Fig. 1). [47] provides other relevant background site information.

The test site was located ~200 m from the Keele University weather observation station, which continually measured daily rainfall and air and ground temperatures as well as having soil temperature probes at 0.1 m, 0.3 m and 1.0 m below ground level. Figure 2 shows a monthly summary of the total rainfall and average temperature data over the monitoring period with temperature data for the zero to three year monitoring study also shown for comparison. The local weather station data showed that total monthly rainfall during the four to six year study period ranged from 2.6 mm to 152.2 mm, with an overall monthly average of 64.7 mm, the same as for the zero to three year monitoring period [47]. Average monthly air temperatures ranged from -1.2 ºC to 12.8 ºC, with an overall monthly average of 5.5 ºC, 3.2 ºC colder than for the zero to three year monitoring period (Fig. 2). However, note at 0.3m bgl the average temperature was 10.2 ºC for the four to six year monitoring period and 9.8 ºC for the

0-3 year monitoring period [47]. Accumulated Degree Day (ADD) data (see [50] for background) detailed in Table 1 quantified these temperature differences.

FIG. 1. -position

FIG. 2. -position

Simulated graves

Five simulated graves were created at the site (Fig. 1A). Three of the graves were used for the repeat geophysical surveys, whilst ground water samples were collected at regular intervals from both the fourth grave and a separate control site situated ~10 m upslope away from the graves (Fig. 1E-F), both of the soilwater sampling sites being outside the geophysical survey area (Fig. 1A). Of the three simulated graves geophysically surveyed, one contained a naked pig carcass, one contained a carcass wrapped in woven PVC tarpaulin and the third was an empty grave to act as a control (Fig. 1). Pig cadavers are commonly used in such monitoring experiments as they comprise similar chemical compositions, size, tissue:body fat ratios and skin/hair type to humans [51,52]. The grave emplacement procedure was described in [47].

Bulk ground water conductivity data collection

Ground water sample lysimeters were emplaced both within a grave containing a pig carcass outside the geophysical survey area and a further lysimeter ~10 m from the survey area to act as control (Fig. 1). The lysimeter emplacement and regular sample collection (Table 1) and analysis procedures used in this study were the same as for the initial three year monitoring period and are described in [47]. The only change was the sample frequency with samples collected at approximately three-monthly seasonal intervals during the four to six year monitoring period due to limited monthly changes observed in the zero to three year monitoring period [47] and survey time constraints (Table 1).

TABLE 1.

Near surface geophysical data collection & processing

Twin electrode (0.5 m fixed-offset) resistivity surveys were conducted at three monthly intervals over the geophysical survey area (Fig. 1A-B) during the four to six year monitoring period (Table 1). Data was collected using the RM15 (Geoscan™ Research) resistivity meter on a 0.25 m by 0.25 m grid with remote probes placed on the same position 17 m from the survey area for consistency. Subsequent data processing methodology was the same as detailed in [47].

A 2D Electrical Resistivity Imaging (ERI) survey line orientated SW-NE (Fig. 1A-B) was surveyed at approximately three-monthly intervals (Table 1). 32 electrodes were placed every 0.5 m along the 15.5 m long survey profile that bisected all three graves (Fig. 1A). Geophysical survey collection using a Campus™ TIGRE system and subsequent inversion using Geotomo™ Res2Dinv v.355 software used in this study were the same as for the initial three year monitoring period and are described in [47].

Due to the variable results of horizontal time slices that GPR data generated in the zero to three year monitoring survey period (see [47]), 2D GPR profiles were only collected on two profiles within the survey area that bisected the two simulated graves with pigs present (Fig. 1A) at approximately three-monthly intervals (Table 1). GPR data collection using the PulseEKKO™ 1000 equipment utilised 110 MHz, 225 MHz, 450 MHz and 900 MHz dominant frequency antennae, with radar trace spacings being 0.2 m, 0.1 m, 0.05 m, and 0.025 m, respectively, using 32 ‘‘stacks’’ to increase the signal-to-noise ratio and for all data sets for consistency purposes. Subsequent data processing were the same as for the initial three year monitoring period and are described in [47].

Results

Table 1 qualitatively summarises the respective geophysical anomaly visibilities in survey results based on [42] methodology of: *None, Poor, Good* and *Excellent*. A score of *None* indicated the respective grave was not detected, with a score of *Poor* showed a slightly discernible geophysical anomaly at the grave location. A score of *Good* demonstrates a clear geophysical anomaly that would be discernible in the field during a geophysical survey and a score of Excellent demonstrates a clearly discernible and prominent anomaly at the grave location.

Bulk ground water conductivity

Background soilwater conductivity measurements demonstrated that background values were consistent over the three year monitoring period (averaging 355 ± 0.1 µS/cm with 40 SD) that was comparable to the zero to three year monitoring period (averaging 444 ± 0.1 µS/cm). However, the pig leachate conductivity continued to reduce during year four (Fig. 3A), varying from 6,670 ± 0.1 µS/cm (1,099 days after burial) down to consistent and comparable background values of 356 ± 0.1 µS/cm after 1,670 days of burial to the end of the monitoring period. Pig leachate conductivity changes during the first three years of burial are reported in [47]. Leachate values in this study could be divided into two clear groupings of conductivity against post-burial days; 840-1,670 burial days (which included some data from the third year of monitoring) and 1,670 burial days to the end of the survey period respectively (Fig. 3A). The first data grouping had a decreasing regression line against burial days with a reasonable fit (R^2 = 0.88), with the second data grouping having a flat regression line, albeit with a relatively poor correlation (R^2 = 0.47) due to its flat nature, evidencing that pig leachate conductivity was consistently at background soilwater values (Fig. 3A).

FIG. 3. - position

Site temperature variation could be removed from raw conductivity values as discussed in [47 Pringle et al. 2012 jfs] by weighting each day by its average daily temperature and then giving each day after burial an accumulated degree day (ADD) following standard methods [50]. This study still had the advantage of having temperature probe measurement data available from the actual mid-cadaver depth (~0.3m bgl) from the nearby meteorological weather station, instead of using average air temperatures (Fig. 2). This again allowed the separation of two data groupings with two linear regression correlations to be generated of conductivity against ADD, with similar fits to those generated against post-burial days (R^2 values of 0.86 and 0.57 respectively), see Fig. 3B.

Twin electrode *(fixed-offset) resistivity*

Bulk ground resistivity surveys acquired over the four to six year monitoring study period were again remarkably consistent, with average fixed-offset survey resistance values of 63.6 Ω (with 47.0 Ω minimum and 99.4 Ω maximum values respectively) (compared to an average of 67.1 Ω for zero to three years), after de-spiking data (only averaged 1.6 anomalous ‘spike’ per survey). The three monthly processed fixed-offset resistivity surveys are graphically shown in Figure 4 (see Fig. 1A for 'grave' locations) and summarised in Table 1.

As found in the zero to three year monitoring datasets, the empty grave which acted as control could not be geophysically detected throughout the survey period (green boxes in Fig. 4). The naked pig grave (red boxes in Fig. 4) was anomalously temporally variable throughout the four to six year monitoring period, mostly comprising a small (<0.6 m^2 SD) amplitude mixed low/high anomaly, when compared to background values (Fig. 4 and Table 1). It only comprised a large anomaly with a low resistivity (coloured blue) in the winter Year 4 dataset that was consistently observed in the zero to three year monitoring datasets (see [40] and Table 1). In contrast, the wrapped pig grave (blue boxes in Fig. 4) showed predominantly a large (>0.6 m^2 SD) amplitude high resistivity anomaly (coloured red/white), when compared to background values, that was mostly *Good* to *Excellent* rating and appeared to have increased in size from the zero to three year monitoring dataset immediately after burial (see [47] and Table 1).

FIG. 4. – position

Electrical resistivity imaging (ERI)

After de-spiking data, electrical resistivity imaging surveys acquired over the four to six year monitoring study period were also again consistent, with average ERI six 'n' level survey resistivity values of 197.0 Ω.m with 106.0 Ω.m minimum and 318.9 Ω.m maximum respectively (compared to an average of 161.8 Ω for zero to three years) A summary of the 2D ERI profiles collected is graphically shown in Figure 5 (see Fig. 1A for profile location) and summarised in Table 1. An average inversion model error (RMS) of 2.1 (with 1.2 minimum and 5.1 maximum) after five iterations again indicated a very good model inversion fit to the collected resistivity values (compared to a RMS of 2.82 for zero to three years),.

The empty grave (marked in Fig. 5) again could be detected throughout the survey period, although, in contrast to the zero to three year monitoring period, it had consistently higher resistivity values, when compared to neighbouring regions (Fig. 5). The naked pig grave was again generally detectable as a consistent *Good* rated anomalous low, when compared to background values up to the end of year five, although thereafter it was difficult to resolve from neighbouring regions (Fig. 5 and Table 1). The wrapped pig grave was surprisingly detectable as a large high *Good* rated resistivity anomaly, when compared to background values, although the anomaly was relatively smaller in the summer and autumn of year's four and five (Fig. 5). In the zero to three year monitoring survey the high resistivity anomaly was relatively smaller (see [47] and Table 1).

FIG. 5. - position

Ground Penetrating Radar (GPR)

The 2D GPR profiles acquired throughout the four to six year monitoring survey period are shown in Figure 6A and 6B (see Fig. 1A for profile locations) and summarised in Table 1. The 110 MHz dominant frequency 2D profiles showed the wrapped pig grave could still be consistently and clearly identified by a strong *Good* to *Excellent* rated hyperbola throughout the survey period (except for year 5 summer), although there was a continual reduction in reflection amplitudes. This was in contrast to the naked pig grave which was either not detectable or at best produced a *Poor* rated hyperbola throughout the survey period (see Fig.6A and 6B and Table 1). There were no clear hyperbolae other than those associated with the target graves within these 2D profiles.

The 225 MHz dominant frequency 2D profiles still showed the wrapped pig grave could be clearly identified by an obvious *Good* to *Excellent* rated hyperbola throughout the four to six year monitoring survey period, although there was also a continual reduction in reflection amplitudes (see Fig.6A and 6B). The second, slightly deeper reflector that was first resolved after 15 months of burial within the wrapped pig grave (see [47]) was still present in this dataset. The naked pig grave was given a *Poor* to *None* rating of hyperbola anomaly throughout the four to six year monitoring survey period although it was possible to detect in the autumn and winter data of year 4 (Fig. 6A/B). As per the zero to three year monitoring survey results [47], there were other, smaller hyperbolae present in the naked pig profiles that were not associated with the target. This would have made it difficult to identify the target grave if the position was not known. However, note they may have been detected if data were collected orthogonally to the primary survey line orientation or indeed if time slices were generated (although the zero to three year survey time slice data detailed in [47] was poor).

The 450 MHz dominant frequency 2D profiles showed the wrapped pig grave could be identified by a *Good* to *Excellent* rated hyperbola throughout the four to six year monitoring survey period, but this had a consistently low amplitude (see Fig.6A and 6B and Table 1). The second, slightly deeper hyperbola observed after 3 months of burial was still present during this survey period. The naked pig grave was rated as *Poor to None rated* detectable as a hyperbola throughout the four to six year monitoring period. There were again numerous other, smaller hyperbolae present in both profiles that were not associated with the target grave which would have made it difficult to identify the target grave if the position was not known. These may, again have been detected if data were collected orthogonally to the primary survey line orientation or indeed if time slices were generated (although the zero to three year survey time slice data detailed in [47] was again poor).

The 900 MHz dominant frequency 2D profiles was rated *Poor* to *None* rated so was difficult to identify the naked pig grave throughout the four to six year monitoring period (see Fig.6A and 6B). There were numerous other, smaller hyperbolae present which would also have made it difficult to locate the target grave, although orthogonal surveys may have been successful.

FIG. 6(A).

FIG. 6(B).

Discussion

This study is the first published research to systematically detail resistivity, GPR and site monitoring data over a simulated clandestine grave test site over six years of burial summarised in Table 1. Importantly both naked and wrapped cadavers have been emplaced and surveyed which provides the two main burial styles encountered in discovered clandestine graves of murder victims. This has allowed questions by forensic search teams listed in the introduction to be answered that has not been able to be undertaken to date. These will be sequentially discussed and are deliberately similar to those posed in the zero to three year monitoring paper [47].

A) Could twin electrode (*fixed-offset) and electrical resistivity imaging surveys still successfully locate the 'naked' and 'wrapped' simulated clandestine burials beyond three years after burial? And if so, how long were they geophysically detectable for?* From the results of this long-term study, the answer was, it still depends on the burial style. The fixed-offset electrical resistivity surveys showed that a naked cadaver(s) has a good chance of being located up to 2.5 years after burial (see Table 1 and [47]), due to the highly conductive grave fluid' producing a consistent low resistance geophysical anomaly when compared to background site resistance values (Fig. 3). This agrees with other resistivity studies over simulated clandestine burials with similar monitoring time periods (see [26,52]. Recent collaborative research comparing the same monitoring experiment on three different University sites in contrasting soil types has evidenced that conductivity measurements of grave fluids could date the burial interval of a discovered clandestine grave in the field if a conductivity meter was available and enough grave fluid was present (see [45]).

However, this study showed that a naked cadaver would be very difficult to detect using fixed-offset electrical resistivity surveys after only four years of burial (Fig. 4) and using ERI surveys after five years of burial (Fig. 5) respectively. The majority of the grave fluids (other than that held by capillary pressure) would migrate away from the cadaver and potentially result in a geophysical anomaly not being over the target, and hence the subsequent search excavation team not finding the target, which would be especially problematic in surveys within significant topographic variation (see [1,30]. In contrast, the wrapped or clothed cadaver(s) essentially largely isolated the target and its conductive grave fluids from the surrounding soil, giving a potential barrier to electrical current. There was therefore a small and temporally varying high resistance anomaly, with respect to background site resistance values, identified over the wrapped target location in the zero to three year monitoring data (see [47]), the varying nature suggested to be caused by some leaking of grave fluids into the surrounding soil. However, this paper detailing the four to six year monitoring data showed a consistent large high resistance anomaly, when compared to background site resistance values, to be present in both the fixed-offset and ERI electrical resistivity datasets over the wrapped cadaver (see Figs. 4 and 5), this consistency presumably due to most grave fluid at this time period being largely absent from the survey area. Note that wrapping a body in plastic or clothing has also been reported by others to slow decomposition [53] and inhibit micro-organism activity [51] which therefore suggests a clandestinely buried body may be identifiable for longer if wrapped in woven PVC tarpaulin as compared to naked.

Using all the resistivity datasets collected in the six year monitoring period, a graphical time-line diagram has been generated to show temporal resistivity anomaly variations (Fig. 7). In terms of optimally configuring fixed-offset resistivity equipment if the likely depth of burial is unknown, modern versions (eg. the Geoscan™ RM-15 used in this study) have the capability to collect and digitally record fixed-offset resistivity data at a variety of probe spacings almost simultaneously at each sampling position (see [54] for forensic resistivity dataset examples). This would therefore not significantly add to survey time if more than one probe spacing data is collected and trace sample spacing could still be comparatively small so that any potential loss in resolution is minimised. The forensic resistivity su\vey results in this paper are in sandy loam soil, with good forensic resistivity survey results also reported in coastal sand [36], chalky [26] and black earth [54] soil types respectively, but relatively poor results in coarse pebble soil types [54].

FIG. 7. - position

B)Could single profile GPR surveys successfully locate both simulated clandestine burials throughout the four to six year monitoring period? And which dominant frequency antenna was optimal to detect them? From the results shown in this four to six year monitoring study, the naked cadaver was not able to be detected on 2D GPR transverse profiles using either the 110 MHz or 900 MHz dominant frequency antennae and was only poorly detectable by the 225 MHz dominant frequency antennae in the autumn to winter datasets (Fig. 6A/B). This was in contrast to the zero to three year monitoring period [47] and other studies undertaken on [47] timescale (e.g. see [38,39,42]). The naked cadaver, however, was detectable as a deeper ½ hyperbolic reflection event in the 450 MHz 2D transverse profiles although this did not have high amplitudes (Fig. 6A/B). In contrast, the wrapped cadaver was detectable on 2D GPR profiles using all the frequencies trialled, namely the 110, 225 and 450 MHz dominant frequency antennae (the 900 MHz antennae was not used over this grave, but it is believed that the grave could have been detected with this frequency based on the other frequency data). This was presumably still due to the wrapping surface allowing stronger GPR reflections to be obtained, with the decomposing naked cadaver attenuating a greater proportion of the GPR signal as other authors have noted (e.g. see [42]). This radar absorption would be exacerbated by the pig-chest cavity having collapsed during decomposition stages as noted in [47], which is a probable explanation for the two GPR hyperbolae still present in 225 and 450 MHz dominant frequency data over the target location (Fig. 6A/B). 225 MHz dominant frequency antennae was shown in this study to be preferable to the other frequencies trialled (110, 450 and 900 MHz frequencies) in the 2D profiles due to a detectable anomaly, target resolution and fewer non-target hyperbolae present in the relative higher frequency data; note also forensic 225 MHz frequency radar surveys also took less time in the field to acquire when compared to their higher frequency versions. This could be an important factor for a forensic search team to consider if the proposed area is significant in size or if manpower and/or budget are limited. This agrees with others (e.g. [42]) who also suggested that 2D GPR profiles should be collected in both orientations over a survey site if possible to have the best chance of detection.

C) When was the optimal time (both up to six years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey? Clearly from the results shown in this study and others (e.g. [42]) the burial style is key, it would be difficult to detect a naked burial after the first 18 months of burial using the resistivity and GPR survey methods detailed here and in [47]. However, note that other studies have shown favourable GPR survey results over much older burials in different ground conditions (eg. ([3,34,54,55]). Whilst there is a general reduction in hyperbola quality in both burial styles, with the naked cadaver being much more difficult to detect, there is a seasonal effect, with autumn and winter surveys, especially in years four to six post burial, generally better at resolving the targets. This has also been observed by authors geophysically monitoring simulated clandestine burials on shorter time scales (e.g. [42]).

The resistivity surveys also showed a similar pattern, especially the fixed-offset electrical resistivity surveys which, when following [46] methodology to numerically measure resistivity anomaly relative areas over time, consistently showed winter surveys were optimal (Table 1). Each autumn to winter the anomalies over both the naked and wrapped cadavers increased in area and reduced in normalised standard deviation (SD) values whereas they were comparably smaller and had larger SD values in the summer months (Fig. 8). The naked cadaver's anomaly and the normalised SD of the datasets got progressively smaller over time, but the wrapped cadaver's relatively high resistance anomaly increased in size over the six year study period (Fig. 8). Temporally varying resistivity anomalies over fixed archaeological targets have also been reported by [56] who undertook time-lapse resistivity surveys over UK Roman fortification defence ditches. This study therefore shows the cyclical nature of low winter/spring SD values and high summer/autumn SD values repeating each year that was most probably due to the soil having reduced moisture content during the warmer and dryer periods but, importantly, in a non-uniform manner for this study site. Thus the 'noise' present within the geophysical data significantly increased during these seasonal periods and effectively 'masked' the target(s). See ([52] and [57] for detailed analysis of site soil moisture for the first two years of burial.

FIG. 8. - position

D) When should a forensic geophysical survey be undertaken in a six year search scenario? From this and other studies (e.g. 38-42,44]), clearly the burial style is still key; although the wrapped grave was initially harder to detect with electrical resistivity surveys (as shown in [47]), in this paper it is relatively easier to detect after four to six years of burial (Fig. 7). The wrapping also makes the target easier to find with GPR as the wrapping makes a good reflective target (Table 1). So although wrapping may help to conceal a body in some ways (for example, it may trap scent and prevent decompositional fluids leaching into the soil), it may also make a body easier to find geophysically. If the burial style is not known, then it is suggested that both electrical and GPR surveys be undertaken to have the best chance of successful detection. Note a naked cadaver would be progressively more difficult to find after 18 months of burial as shown in this (Table 1) and other studies (see [38-42,44]), and therefore other complementary methods should be trialled (e.g. search cadaver dogs).

This study also reinforces other research (see e.g. 38-42,44,56]) the importance of when a forensic geophysical survey should be conducted within the year, seasonality has shown to be surprisingly important, and, if operational time permits, then geophysical surveys should be undertaken in winter to have the best chance of target detection success. If a past forensic geophysical search was unsuccessful, perhaps the results should be reviewed in terms of seasonality and perhaps re-surveyed if the original survey season was unfavourable. If there is a time-restricted element to the forensic search, then the season of surveying should be undertaken and an appropriate alternative search method should be chosen if necessary.

From this long-term simulated grave monitoring study and comparing results from [24,27],29,38-42, 44,57-60], we still recommend that forensic geophysical surveys should be undertaken prior to other, more invasive search methods (e.g. metal detectors, soil/methane probes and cadaver dog probes). Any resulting soil disturbances from these surveys would lead to more false positives for the resulting geophysical surveys, as found during the [29] forensic resistivity search. Once anomalous geophysical areas within the survey area are identified, these should be prioritised and then subjected to more detailed scientific investigations, which includes geophysical surveys (e.g. 2D ERI profiles, higher frequency 2D/3D GPR surveys), cadaver dogs, invasive probing, etc. See [11] for other geoscience search methods and suggested phased investigative approaches.

Conclusions and further work

Geophysical long-term monitoring survey results over the simulated clandestine burials shown in this study and by others in different soil types should be used both to assist forensic search investigators to use the appropriate search technique and equipment configuration, and indeed as a reference to allow comparison of data collected by forensic search investigators looking for similar clandestine burials of murder victims.

A *buried 'naked' victim* within a clandestine burial, if shallowly buried, should be able to be located within the first 4 years of burial using twin electrode electrical resistivity surveys. If the burial depth is unknown, the use of wider electrode separations in addition to the most frequently used 0.5 m spacing is recommended. Resistivity surveys are also recommended to be undertaken in clay-rich soils over GPR surveys due to the likelihood of highly conductive 'leachate' being retained in the surrounding soil and GPR experiencing poor penetration depths in these soil types. However after this time period a naked victim would become progressively more difficult to locate using electrical methods, with the majority of the decompositional fluids migrating away from the target, depending upon the soil type. However, ERI 2D profiles could potentially still locate naked victims up to five years of burial if sited over it. 110 – 225 MHz dominant frequency GPR surveys could detect targets well up to 18 months of burial, then 225 MHz frequency poorly in winter months up to five years of burial due to decomposition, although skeletal material may still be imaged depending on target(s) depth and specific site conditions. If time and manpower availability permits then winter surveys should be undertaken.

A *buried 'wrapped' or clothed victim* within a clandestine burial, if shallowly buried, should be able to be located using both fixed-offset electrical resistivity and ERI 2D Profile surveys throughout the six year monitoring period; in fact in this study it became progressively easier to detect the wrapped cadaver as the burial period extended. Medium (225-450 MHz) dominant frequency GPR antennae were deemed optimal frequency for detection due to good target resolution as other authors have evidenced (e.g. [41-42]); less non-target anomalies and data acquisition speed, although 110 MHz and 450 MHz frequency antennae data also resolved the wrapped grave throughout the study period, most probably due to the 'wrapping' producing a good reflective contrast. If time and manpower availability permits then winter surveys should be undertaken.

This study site will be continued to be monitored annually to discover *at what time* period after burial will geophysical surveys not be able to determine the location of a clandestine burial. Organic, inorganic and other analytical measurements are currently being undertaken to examine what may be causing the variability in grave 'soilwater' conductivity after burial with preliminary results looking promising [61].

Further analysis of the geophysical data will also be undertaken; both to determine if there are diagnostic GPR signal spectra for clandestine burials versus background signals and to determine if both GPR and resistivity datasets can be simultaneously inverted numerically to quantify anomaly location(s), sizes and to quantitatively combine these two geophysical search techniques.

This experimental methodology should be repeated on similar time scale in other, contrasting soil types, in order to determine if soil type is a major factor in the ability of forensic geophysical surveys to successfully locate a clandestine burial. On a longer time scale, it is planned that the experiment will be repeated using human cadavers rather than pig analogues, as this may be an important variable to consider.

Acknowledgements

We acknowledge ex-Keele PhD student Tim Millington and Keele University technical staff Malcolm Wright for assistance in creating the study site and Ian Wilshaw for assistance in installing the lysimeters and providing local weather data. Numerous Keele University undergraduate and postgraduate students assisted in collecting geophysical data during this study, together with Giulia di Mascio from Polimi University, Italy. Colin Hope of the U.K. National Crime Agency (NCA) is thanked for operational search advice.

References:

1. Harrison M, Donnelly LJ. Locating concealed homicide victims: developing the role of geoforensics. In: Ritz K, Dawson L, Miller D, editors. Criminal and Environmental Soil Forensics, Dordrecht: Springer, 2009;197–219.

2. Larson DO, Vass A A, Wise M. Advanced scientific methods and procedures in the forensic investigation of clandestine graves. J Contemp Crim Justice 27 2011;27:149–82.

3. Davenport GC. Remote sensing applications in forensic investigations. Hist Arch 2001;35:87–100.

4. Killam EW. The detection of human remains. Springfield: Charles C Thomas, 2004.

5. Dupras TL, Schultz JJ, Wheeler SM, Williams LJ. Forensic recovery of human remains: archaeological approaches. 2nd ed, Boca Raton, FL: CRC Press, 2011.

6. Rebmann A, David E, Sorg MH. Cadaver dog handbook: forensic training and tactics for the recovery of human remains. Boca Raton:CRC Press, 2000.

7. Lasseter A, Jacobi KP, Farley R, Hensel L. Cadaver dog and handler team capabilities in the recovery of buried human remains in the Southeastern United States. J For Sci 2003;48:1–5.

8. Pye K, Croft, DJ. Forensic Geoscience: Principles, Techniques and Applications. London: Geol Soc London Spec Pub 232, 2004.

9. Ruffell A, McKinley J. Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations. Earth Sci Rev 2005;69:235–47.

10. Ruffell A, McKinley J. Geoforensics. Chichester: Wiley, 2008.

11. Pringle JK, Ruffell A, Jervis JR, Donnelly L, McKinley J, Hansen J, Morgan R, Pirrie D, Harrison M. The use of geoscience methods for terrestrial forensic searches. Earth Sci Rev 2012a;114:108-23.

12. Davenport GC, Griffin TJ, Lindemann JW, Heimmer D. Geoscientists and law enforcement officers work together in Colorado. Geotimes 1990;35:13–5.

13. Brilis GM, Gerlach CL, van Waasbergen RJ. Remote sensing tools assist in environmental forensics. Part I. Digital tools—traditional methods. Env For 2000a;1:63–7.

14. Brilis GM, van Waasbergen RJ, Stokely PM, Gerlach CL. Remote sensing tools assist in environmental forensics. Part II. Digital tools. Env For 2000b;1:1–7.

15. Hunter J, Cox M. Forensic archaeology: advances in theory and practice. Abingdon: Routledge, 2005.

16. Dickinson DJ. The aerial use of an infrared camera in a police search for the body of a missing person in New Zealand. J For Sci Soc 1976;16:205–11.

17. Ruffell A, McKinley J. Forensic geomorphology. Geomorph 2014;206:14-22.

18. Owsley DW. Techniques for locating burials, with emphasis on the probe. J For Sci 1995;40;735–40.

19. Ruffell A. Burial location using cheap and reliable quantitative probe measurements. For Sci Int 2005a;151:207-11.

20. Hunter J, Simpson B, Sturdy Colls C, Forensic approaches to buried remains (essential forensic science). Chichester: Wiley, 2013.

21. Reynolds JM. An introduction to applied and environmental geophysics, 2nd ed, Chichester: Wiley-Blackwell, 2011.

22. Mellet JS. Location of human remains with ground penetrating radar. In: Hanninen, P, Autio S, editors. Proc Fourth Int Conf on GPR, 1992 Jun 8-13; Rovaniemi, Geological Surv Finland Spec Paper 16;359–65.

23. Calkin SF, Allen RP, Harriman MP. Buried in the basement – geophysics role in a forensic investigation. Proc of symp Appl Geophys Eng environ problems; 1995, Denver: Env Eng Geophys Soc;397–403.

24. Nobes DC. The search for ‘‘Yvonne’’: a case example of the delineation of a grave using near-surface geophysical methods. J For Sci 2000;45:715–21.

25. Scott J, Hunter JR. Environmental influences on resistivity mapping for the location of clandestine graves. In: Pye K, Croft DJ, editors. Forensic Geoscience: Principles, Techniques and Applications. London: Geol Soc London Spec Pub 2004;232:33–8.

26. Cheetham P. Forensic geophysical survey. In: Hunter J, Cox M, editors. Forensic Archaeology: Advances in Theory and Practice, Abingdon: Routledge, 2005;62–95.

27. Ruffell A. Searching for the IRA “disappeared”: Ground Penetrating radar investigation of a churchyard burial site. J For Sci 2005;50:1430-5.

28. Schultz JJ. Using ground-penetrating radar to locate clandestine graves of homicide victims: forming forensic archaeology partnerships with law enforcement. Homicide Studies 2007;11:15-29.

29. Pringle JK, Jervis JR. Electrical resistivity survey to search for a recent clandestine burial of a homicide victim, UK. For Sci Int 2010;202(1-3):e1-7.

30. Novo A, Lorenzo H, Ria F, Solla M. 3D GPR in forensics: finding a clandestine grave in a mountainous environment. For Sci Int 2011;204:134-8.

31. Schultz JJ. The application of GPR for forensic grave detection. In: Dirkmaat DC, editors. A companion to forensic anthropology, Hoboken, NJ: Blackwell, 2012, p.85-100.

32. Ruffell A, Pringle JK, Forbes S. Search protocols for hidden forensic objects beneath floors and within walls. For Sci Int 2014;237:137-45.

33. France DL, Griffin TJ. Swanburg JG, Lindemann JW, Davenport GC, Trammell V. et al. A multidisciplinary approach to the detection of clandestine graves. J For Sci 1992;37:1445–58.

34. Strongman KB. Forensic applications of ground penetrating radar. In: Pilon J, editor. Ground Penetrating Radar, Ottawa: Geological Survey of Canada Paper 90-4, 1992;203–11.

35. Freeland RS, Miller ML, Yoder RE, Koppenjan SK. Forensic applications of FMCW and pulse radar. J Env Eng Geophys 2003;8:97–103.

36. Pringle JK, Holland C, Szkornik K, Harrison M. Establishing forensic search methodologies and geophysical surveying for the detection of clandestine graves in coastal beach environments. For Sci Int 2012;219:e29-e36.

37. Pringle JK, Wisniewski K, Giubertoni M, Cassidy NJ, Hansen JD, Linford NJ, Daniels RM. The use of magnetic susceptibility as a forensic search tool. For Sci Int 2015a;246:31-42.

38. Schultz JJ, Collins ME, Falsetti AB. Sequential monitoring of burials containing large pig cadavers using ground-penetrating radar. J For Sci 2006;51:607–16.

39. Schultz JJ. Sequential monitoring of burials containing small pig cadavers using ground-penetrating radar. J For Sci 2008;53:279–87.

40. Pringle JK, Jervis J, Cassella JP, Cassidy NJ. Time-lapse geophysical investigations over a simulated urban clandestine grave. J For Sci 2008;53:1405-17.

41. Schultz JJ, Martin MM. Controlled GPR grave research: Comparison of reflection profiles between 500 and 250 MHz antennae. For Sci Int 2011;209:64-9.

42. Schultz JJ, Martin MM. Monitoring controlled graves representing common burial scenarios with ground penetrating radar. J App Geophys 2012;83:74-89.

43. Schotmans EMJ, Fletcher JN, Denton J, Janaway RC, Wilson AS. Long-term effects of hydrated lime and quicklime on the decay of human remains using pig

cadavers as human body analogues: Field experiments. For Sci Int 2014a;238:141.e1-e13.

44. Molina CM, Pringle JK, Saumett M, Hernandez O. Preliminary results of sequential monitoring of simulated clandestine graves in Colombia, South America, using ground penetrating radar and botany.For Sci Int 2015;248:61-70.

45. Pringle JK, Cassella JP, Jervis JR, Williams A, Cross P, Cassidy NJ. Soilwater conductivity analysis to date and locate clandestine graves of homicide victims. J For Sci in press.

46. Jervis JR, Pringle JK. A study of the affect of seasonal climatic factors on the electrical resistivity response of three experimental graves. J App Geophys 2014;108:53-60.

47. Pringle JK, Jervis JR, Hansen JD, Cassidy NJ, Jones GM, Cassella JP. Geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 0-3 years. J For Sci 2012b;57:1467-86.

48. Manhein MH. Decomposition rates of deliberate burials: a case study of preservation. In: Haglund WD, Sorg MH, editors. Forensic taphonomy: the post-mortem fate of human remains, Boca Raton, FL: CRC, 1996;469–81.

49. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydro Earth Sys Sci 2007;11:1633–44.

50. Vass AA, Bass WM, Wolt JD, Foss JE, Ammons JT. Time since death determinations of human cadavers using soil solution. J For Sci 1992;37:1236–53.

51. Carter DO, Tibbett M. Cadaver decomposition and soil: processes. In: Tibbett M, Carter DO, editors. Soil Analysis in Forensic Taphonomy: Chemical and Biological Effects of Buried Human Remains. Boca Raton: CRC Press, 2009;29–52.

52. Jervis JR, Pringle JK, Tuckwell GT. Time-lapse resistivity surveys over simulated clandestine burials. For Sci Int 2009;192:7-13.

53. Rodriguez WC. Decomposition of buried and submerged bodies. In: Haglund WD, Sorg MH, editors. Forensic Taphonomy: The Postmortem Fate of Human Remains. Boca Raton: CRC Press, 1997;459–68.

54. Hansen JD, Pringle JK, Goodwin J. GPR and bulk ground resistivity surveys in graveyards: locating unmarked burials in contrasting soil types. For Sci Int 2014;237:e14-e29.

55. Bevan BW. The search for graves. Geophysics 1991;56:1310–9.

56. Clark AJ. Seeing beneath the soil: prospecting methods in archaeology, 2nd rev. ed. New York: Routledge, 1996.

57. Jervis JR. The detection of clandestine graves using electrical resistivity surveys: results from controlled experiments and a case study (PhD dissertation). Keele: Keele University, 2011.

58. Ellwood BB, Owsley DW, Ellwood SH, Mercado-Allinger PA. Search for the grave of the hanged Texas gunfighter, William Preston Longley. Hist Arch 1994;28:94-112.

59. Ruffell A, McCabe A, Donnelly C, Sloan B. Location and assessment of an historic (150-160 years old) mass grave using geographic and ground penetrating radar investigation, NW Ireland. J For Sci 2009;54:382-94.

60. Powell K. Detecting human remains using near-surface geophysical instruments. Expl Geophys 2004;35:88–92.

61. Blom G, Davidson A, Pringle J, Williams A, Lamont A, Cassella JP. Chemical markers for the detection of clandestine graves – development of a complimentary technique for forensic geophysics? Recent Work in Arch Geophys and For Geosci: Future Horizons Conf, Geol Soc London, 2-3 December, 2014.

FIGURE CAPTIONS:

FIG. 1. (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI 2D profile lines, lysimeter positions and UK location map all shown (inset). (B) Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and (F) soil fluid measurement photographs respectively. Modified from [47].

FIG. 2. Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the four to six year study period. Dashed average temperature line is for zero to three years survey period [47] shown for comparison.

FIG. 3. (A) Measured pig leachate (diamonds) and background (triangles) soil-water fluid conductivity values over the 6-year survey period; 4-6 years to the right of the vertical dotted line. (B) Measured soil-water conductivity versus accumulated degree day (ADD) plot produced from (A) by summing average daily 0.3 m bgl after burial temperatures (see text). Best-fit linear correlation formulae and confidence (R2) values are also shown. Modified from [47].

FIG. 4. Fixed-offset processed electrical resistivity datasets for the four to six year study period (year and season shown). Red, green and blue rectangles indicate positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).

FIG. 5. Individually inverted 2D Electrical Resistivity Imaging (ERI) Wenner array (0.5 m spaced electrode) profiles for the four to six year study period (year and season

shown); model inversion errors (RMS) for the fifth iterations are indicated. Positions of naked pig, empty and wrapped pig graves are also shown (dashed lines). See Fig. 1A (ERI/ERI') for location.

FIG. 6(A). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 39 – 54 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).

FIG. 6(B). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 57 – 72 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).

FIG. 7. Summary qualitative analysis plot of resistivity data over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed lines (see key and text). Modified from [47].

FIG. 8. Summary quantitative analysis plots of fixed-offset resistivity data collected over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed line. (A) Standard deviations (SD) for each survey, note SD values are highest in late summer; residual volume analysis of (B) naked pig cadaver and (C) wrapped pig cadaver (see text). Modified from [46].

TABLE CAPTION:

TABLE 1. Summary of geophysical surveys and their respective geophysical anomalies in this study (4-6 year results below horizontal line). +Burial date was 7th December 2007. *ADD date based on average daily site temperatures at 0.3 m bgl (see [47]).

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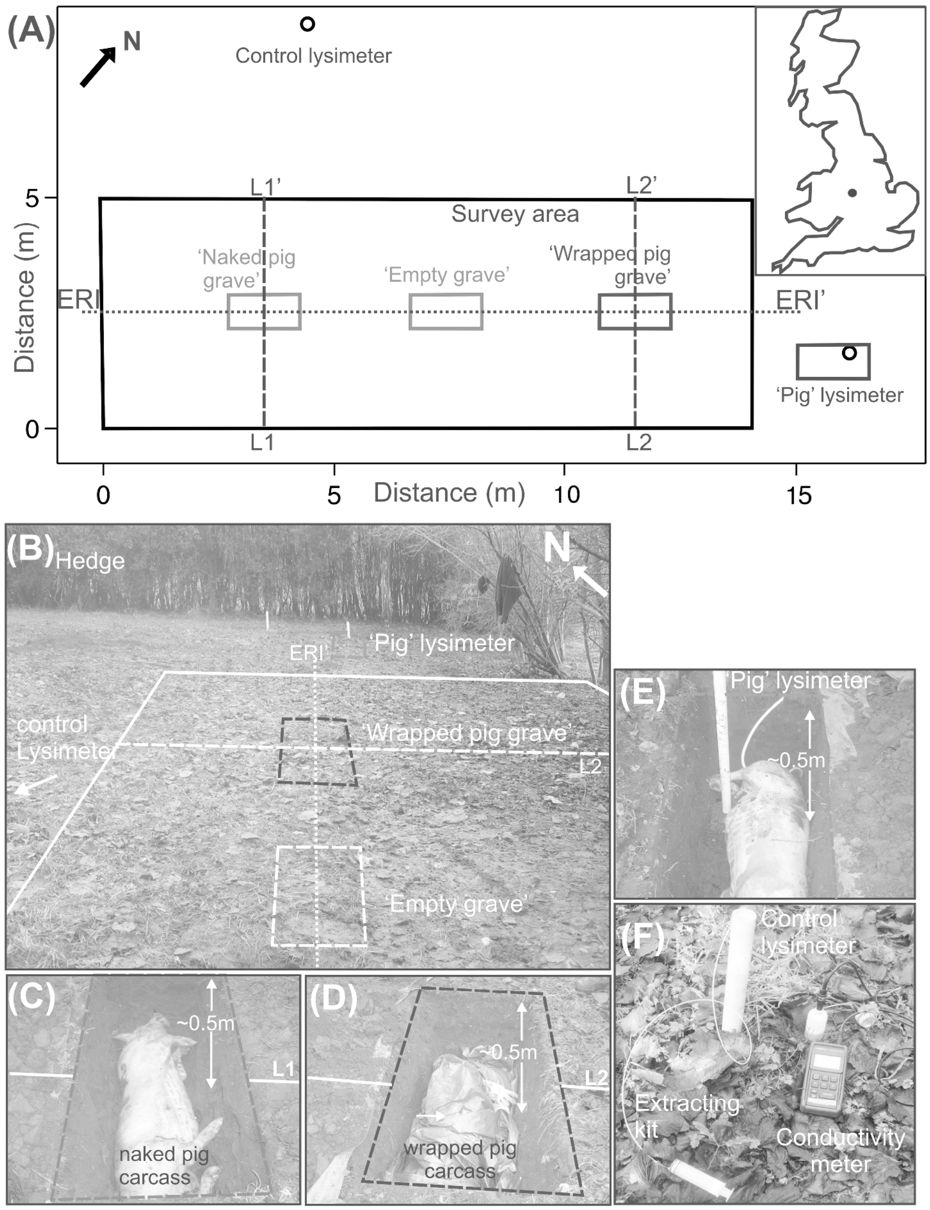

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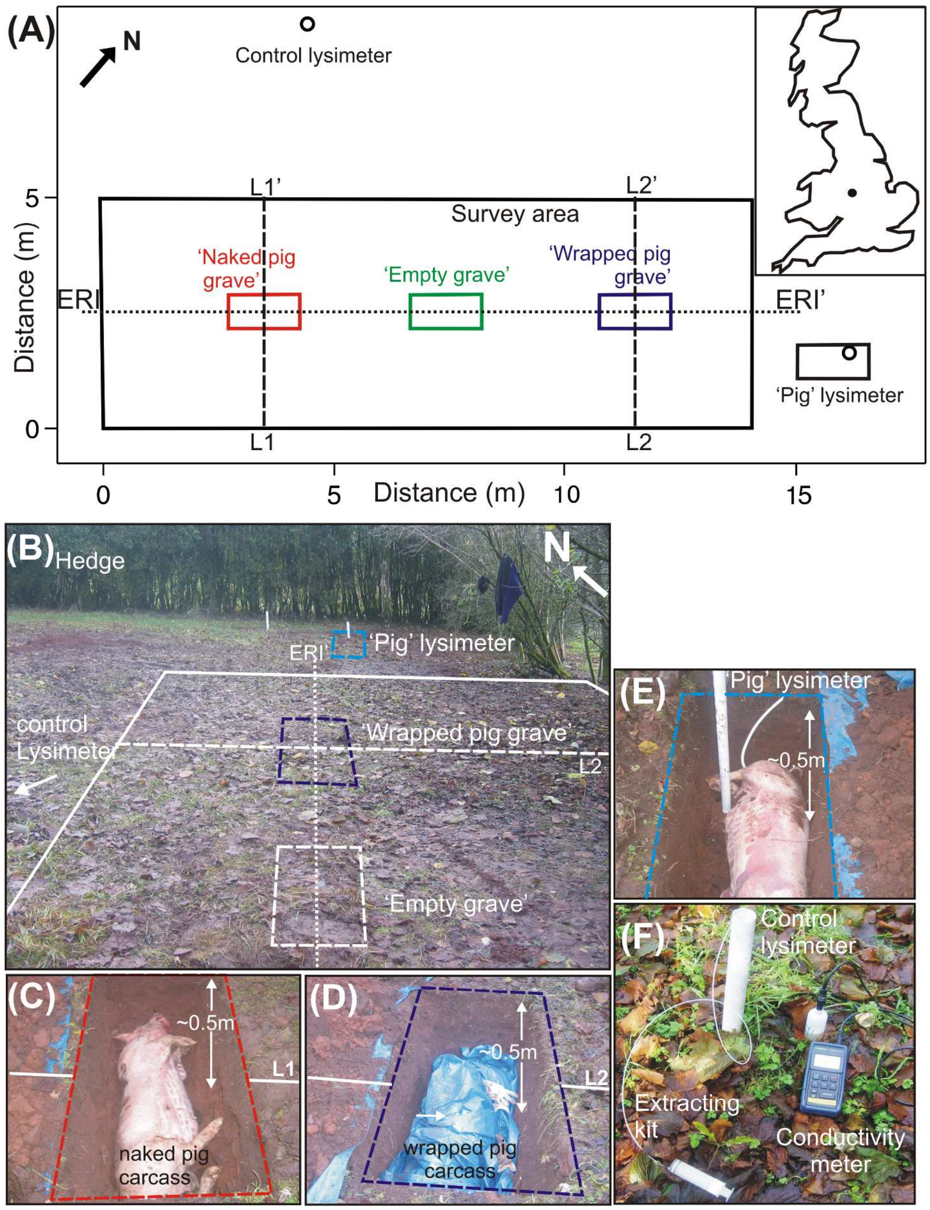

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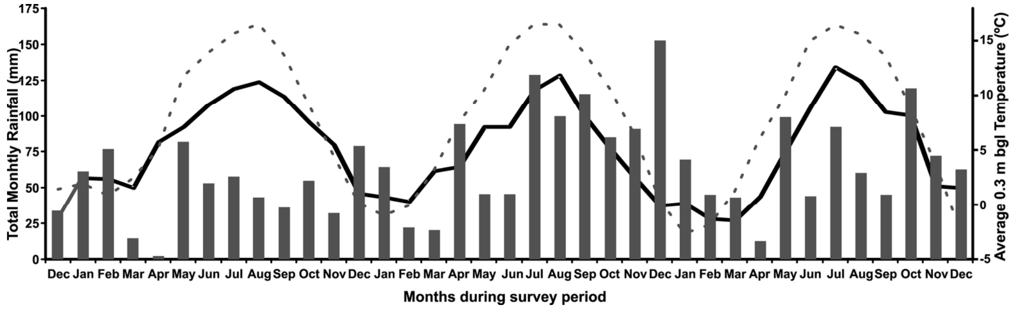
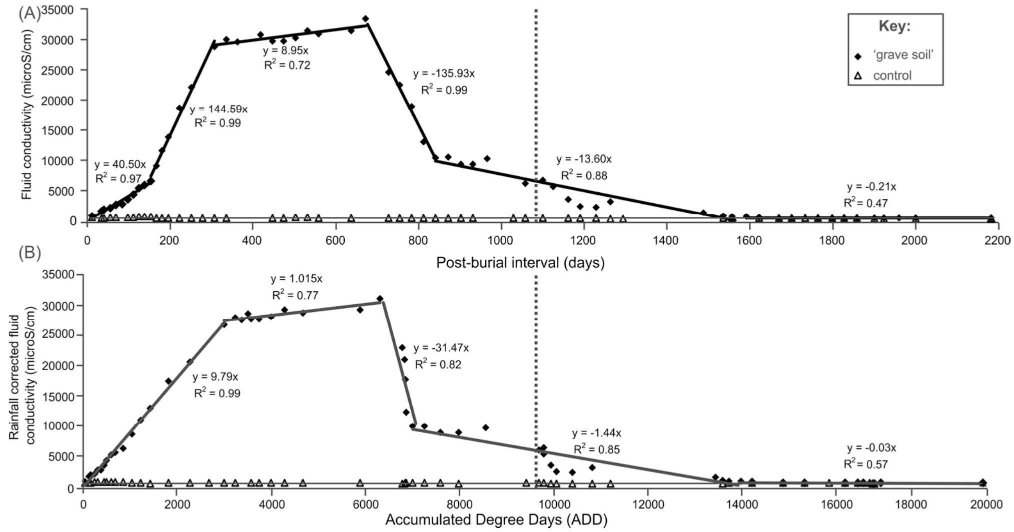


FIG. 2. Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the four to six year study period. Dashed average temperature line is for zero to three years survey period (40) shown for comparison.
86x25mm (600 x 600 DPI)



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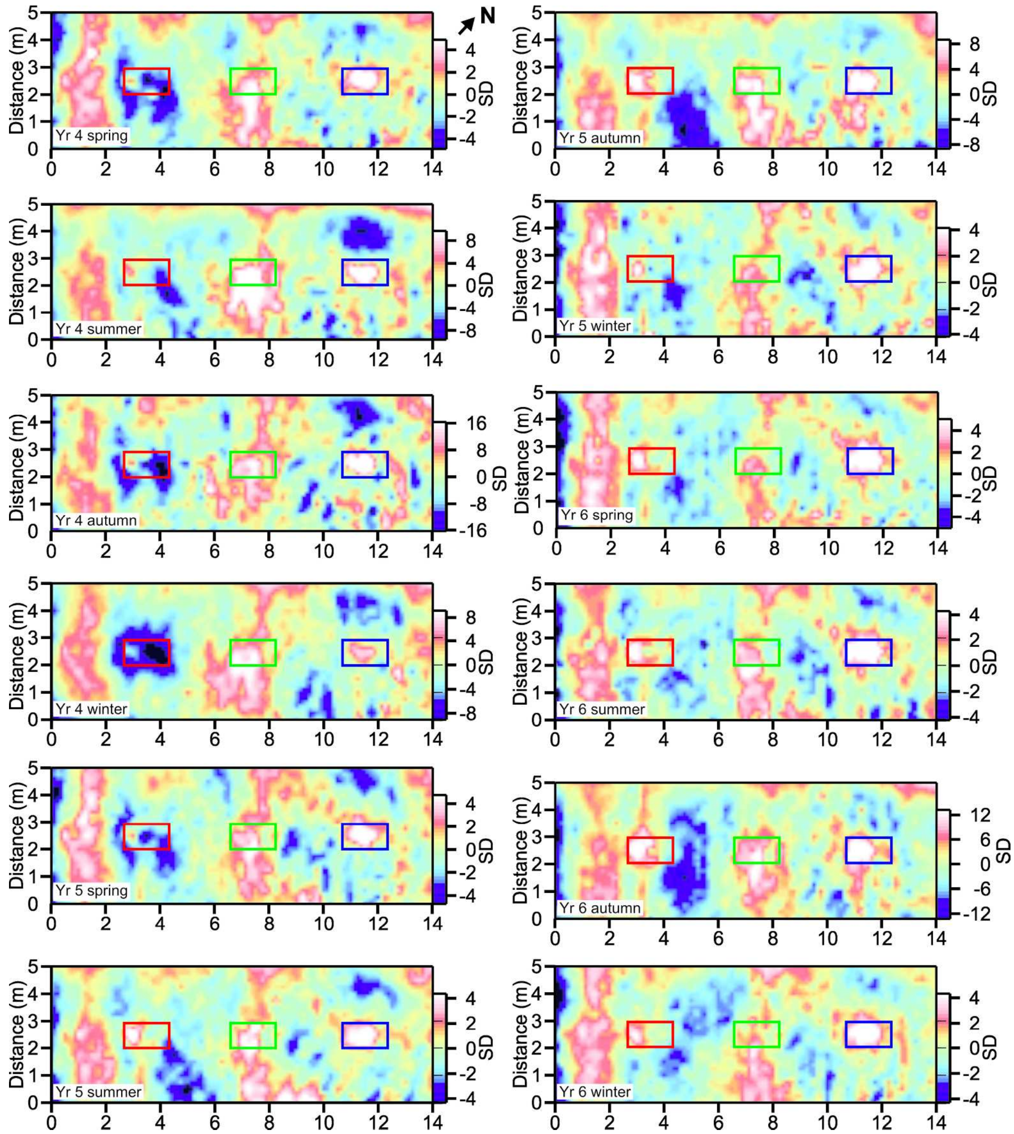
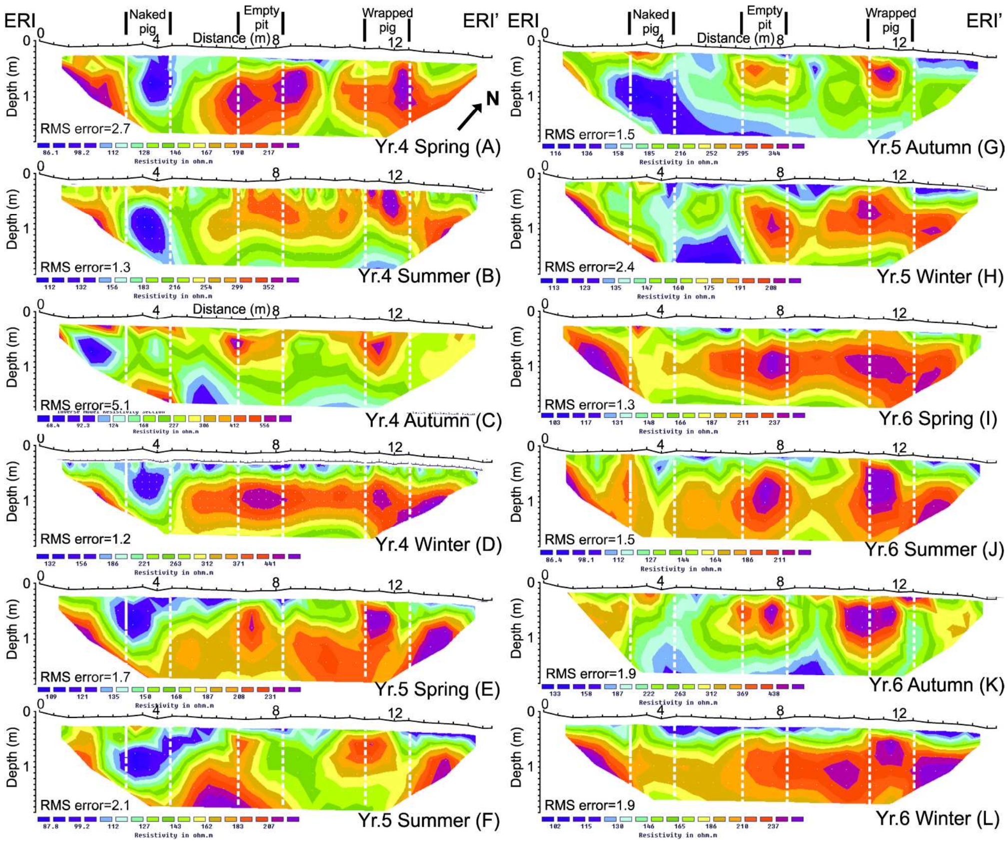


FIG. 4. Fixed-offset processed electrical resistivity datasets for the four to six year study period (year and season shown). Red, green and blue rectangles indicate positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).
209x235mm (300 x 300 DPI)



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214x179mm (300 x 300 DPI)

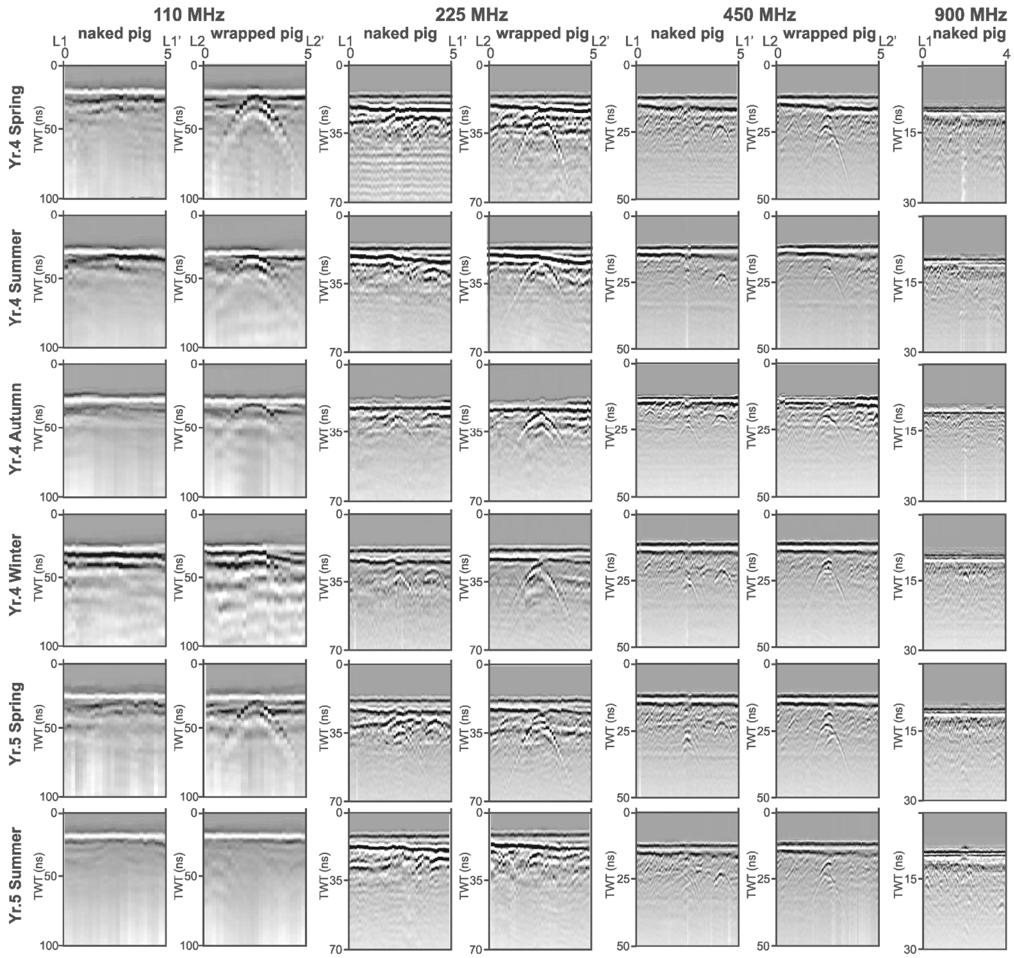

FIG. 6(A). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 39 – 54 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).

313x295mm (300 x 300 DPI)

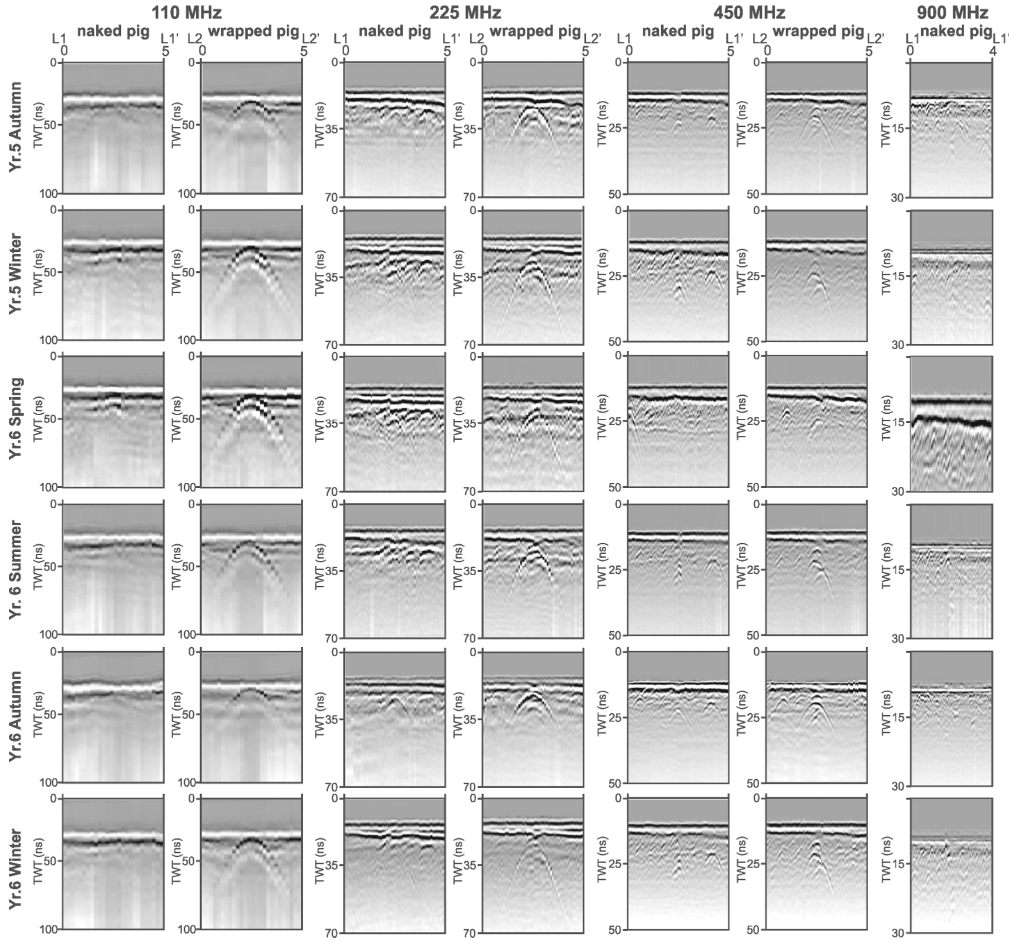

FIG. 6(B). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 57 – 72 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).
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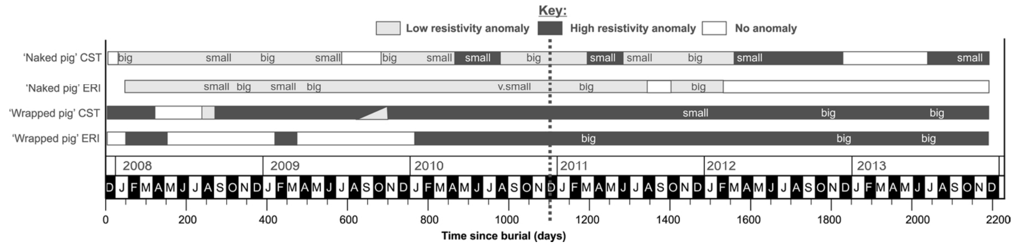

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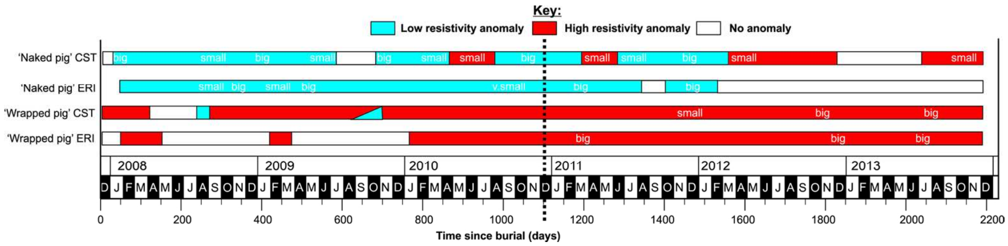
76x18mm (600 x 600 DPI)



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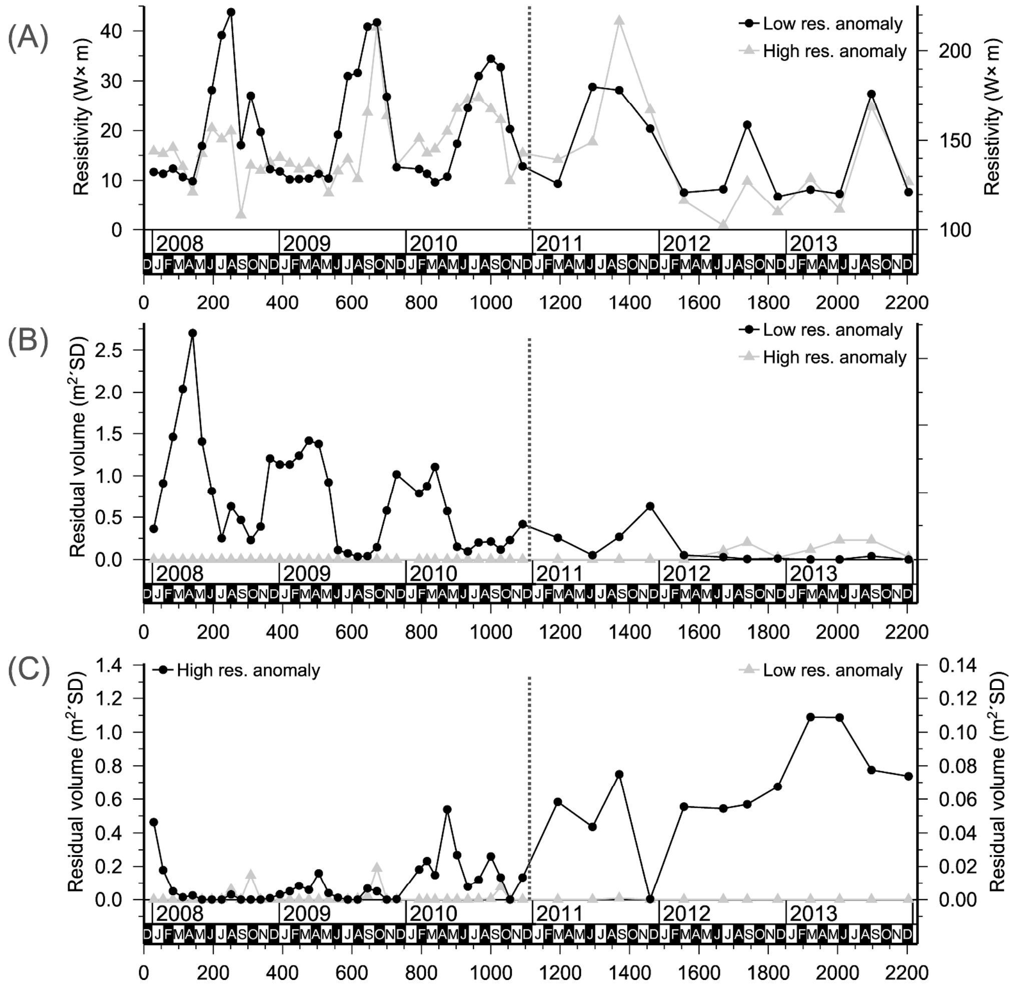

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176x171mm (600 x 600 DPI)

Survey date(s)^	Survey day after burial+	Accum-ulated Degree Day (ADD)*	Twin electrode (0.5m) array (Fig.4)		ERI profile (Fig. 5)		110 MHz (Fig.6)		225 MHz (Fig.6)		450 MHz (Fig.6)		900 MHz
			Naked pig	Wrapped pig	Naked pig	Wrapped pig	Naked pig	Wrapped pig	Naked pig	Wrapped pig	Naked pig	Wrapped pig	Naked pig
07.03.2008	91	454	None	Excellent	Poor	Good	Good	Excellent	Good	Excellent	Poor	Excellent	Poor
05.06.2008	181	1,314	Excellent	Poor	Poor	None	Good	Excellent	Poor	Excellent	Poor	Excellent	None
01.09.2008	269	2,727	Excellent	Poor	Good	None	Poor	Excellent	Poor	Excellent	Poor	Excellent	Good
04.12.2008	363	3,732	Excellent	None	Excellent	None	Good	Excellent	Good	Excellent	Good	Excellent	Good
06.03.2009	455	4,080	Excellent	Poor	Good	Poor	Poor	Excellent	Poor	Excellent	Poor	Excellent	None
20.05.2009	530	4,765	Excellent	Poor	Excellent	Poor	Poor	Excellent	Poor	Excellent	Poor	Excellent	None
11.08.2009	613	6,083	Excellent	Poor	Excellent	Poor	Poor	Excellent	Poor	Excellent	Poor	Good	None
13.11.2009	707	7,371	Poor	Poor	Poor	None	Poor	Excellent	None	Excellent	None	Good	None
20.04.2010	865	8,084	Excellent	Good	Excellent	Poor	Poor	Excellent	None	Excellent	None	Good	None
28.06.2010	934	8,976	Poor	Poor	Excellent	Poor	Poor	Good	None	Good	None	Poor	None
28.09.2010	1,026	11,026	Poor	Good	Poor	Good	Poor	Excellent	None	Excellent	None	Good	None
03.12.2010	1,092	11,026	Good	Good	Excellent	Good	None	Excellent	None	Excellent	None	Poor	None
15.03.2011	1,194	11,401	Good	Good	Excellent	Good	Poor	Excellent	None	Excellent	Poor	Excellent	None
22.06.2011	1,293	12,554	None	Good	Excellent	Good	Poor	Excellent	None	Excellent	None	Good	None
09.09.2011	1,370	13,791	Good	Poor	None	Poor	Poor	Good	Poor	Excellent	Poor	Good	None
06.12.2011	1,460	14,827	Excellent	Poor	Good	Poor	None	Good	Poor	Excellent	Poor	Excellent	Poor
12.03.2012	1,557	15,294	Good	Good	Good	Good	Poor	Excellent	Poor	Excellent	Poor	Good	Poor
03.07.2012	1,670	16,577	None	Good	Good	Good	None	Poor	None	Poor	None	Good	None
10.09.2012	1,739	17,750	Poor	Poor	Poor	Good	Poor	Good	None	Good	None	Good	Poor
07.12.2012	1,827	18,636	None	Good	None	Poor	Poor	Excellent	None	Excellent	None	Good	None
12.03.2013	1,922	19,030	Poor	Excellent	None	Good	Poor	Excellent	None	Good	Poor	Good	None
04.06.2013	2,006	19,668	Poor	Excellent	None	Excellent	None	Good	None	Good	Poor	Good	None
04.09.2013	2,098	21,212	Good	Excellent	None	Excellent	None	Good	Poor	Good	Poor	Good	None
18.12.2013	2,204	22,345	Poor	Excellent	None	Good	Poor	Good	None	Good	None	Good	None

TABLE 1. Summary of geophysical surveys and their respective geophysical anomalies in this study (4-6 year results below horizontal line). +Burial date was 7th December 2007. *ADD date based on average daily site temperatures at 0.3 m bgl (see [47]).

Long-term ~~G~~geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 4-6 years after burial

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ABSTRACT

This ongoing monitoring study provides forensic search teams with systematic geophysical data over simulated clandestine graves for comparison to active cases. Simulated 'wrapped', 'naked' and 'control' burials were created. Multiple geophysical surveys were collected over six-years, here showing data from four to six years after burial. Electrical resistivity (~~fixed-offset~~twin electrode and ERI), multi-frequency GPR, grave and background soilwater were collected. Resistivity surveys revealed the naked burial had low-resistivity anomalies up to year four but then difficult to image, whereas the wrapped burial had consistent large high-resistivity anomalies. GPR 110-900 MHz frequency surveys showed the wrapped burial could be detected throughout, but the naked burial was either not detectable or poorly ~~to not~~ resolved. 225 MHz frequency GPR data were optimal. Soil water analyses showed decreasing (year four-five) to background (year six) conductivity values. Results suggest both resistivity and GPR surveying if burial style unknown, with winter to spring surveys optimal and increasingly important as time increases.

Keywords: forensic science; forensic geophysics; clandestine grave; monitoring; electrical resistivity; ~~G~~ground ~~P~~penetrating ~~R~~radar; conductivity

Forensic search methods vary widely, for example, in the UK a search strategist is usually involved in a case at an early stage to decide upon the highest probability of search success [1], whereas in other countries a search may not be methodical, investigations may not be standardised and a variety of techniques are undertaken, depending upon local experience [2]. Metal detector search teams [3-5] and specially trained search dogs [5-7] are both commonly used during either initial investigations or as part of a phased sequential programme.

Forensic investigators have been increasingly using geoscientific methods to aid in civil or criminal forensic investigations, predominantly to assist search teams or for trace evidence purposes [8-11]. One key and high-profile 'target' for forensic search teams to detect and locate is human remains buried within clandestine graves [1,5,12]. These searches generally start from large-scale remote sensing methods [13-14], aerial and ultraviolet photography [10,15], thermal imaging [16], to ground-based observations of vegetation changes [4], surface geomorphology changes [17], soil type [1] and depositional environment(s) [10], near-surface geophysics [11], diggability surveys [1] and probing of anomalous areas [18,19] before topsoil removal [4], and finally controlled excavation and recovery [5,15,20]. A typical search will only use a few of these techniques, depending on the circumstances of each case (Colin Hope, *pers. comm.*).

Near-surface geophysical methods rely on there being a detectable physical contrast between the target and the background (or host) materials (see [21]). Near-surface geophysical surveys have been used to try and locate clandestine graves in a number of reported criminal search investigations [3,5,22-32]. Geophysical surveys collected over simulated burials have been undertaken in order to collect control data (e.g. [33-37]. These studies have shown that the resulting geophysical responses could be well predicted, although responses seem to vary both temporally after burial and between different study sites. A few studies have also collected repeat (time-lapse) geophysical surveys over controlled experiments (e.g. [26,38-44]), which have documented temporal changes in geophysical responses over their study periods. However, uncertainties still remain over what and how long temporal variations occur in geophysical surveys after burial, with study survey sites needing to be fully characterised (e.g. geologically and climatologically) to allow comparisons with other studies or indeed for active forensic cases. Documenting temporal changes is important as geophysical responses from recent clandestine burials are known to vary more than ~~for~~ archaeological graves. Potential reasons for this could be the temporal changes in grave soil characteristics, decomposition products [45], climatic variations, soil moisture content [46] and other site specific factors (see [11]).

This study continued the systematic assessment of the changing geophysical response of simulated clandestine graves during four to six years after burial. Geophysical survey results from zero to three years after burial were published in [47]. A clandestine grave was defined in this study as an unrecorded burial that has been hand-excavated and dug <1 m depth below ground level (bgl). It should be noted that geophysical results will vary depending upon the depth of burial and indeed on local soil type as [11] reviews. The discovered graves published in [15,48] were usually rectangular in plan-view, mostly hurriedly hand dug using garden implements and usually just large enough to deposit the victim before being back-filled with excavated soil and associated surface debris. [48] also detailed that almost half of the 87 documented U.S. cases were either clothed or encased in material (plastic or fabric), so the authors decided to use two end member scenarios for this study; namely one burial containing a *naked* cadaver and another containing a cadaver *wrapped* in a tarpaulin. It is, however, emphasised that these obviously do not represent all types of potential style of burial with [42] considering other scenarios.

There are many potential near-surface geophysical search techniques that could be utilised to search for clandestine graves that the [47] monitoring paper summarises; this ongoing study has concentrated on collecting electrical resistivity (fixed-offset and Electrical Resistivity Imaging 2D profiles) and Ground Penetrating Radar (110 – 900 MHz frequency 2D profiles. Resistivity surveys showed consistent low anomalies, compared to background values, for a naked burial, in contrast with the wrapped burial which had smaller and varied low/high anomalies and was thus harder to locate [47]. Analyses of decompositional fluids showed highest conductivity values, compared to background soilwater, was ~1 year to ~2 years after burial before subsequently decreasing [47]. GPR surveys finally showed low frequency antennae were consistently optimal for target detection [47].

The aims of this continued four to six year geophysical monitoring study of different simulated burial style clandestine burials were to answer some basic questions posed by forensic search teams. Appropriate site data (rainfall, temperature, soil and 'grave' water conductivities) were also continued to be simultaneously collected in order to allow comparisons with other research studies and criminal search investigations. Basic forensic search questions which ~~will~~ were continued to be addressed by this study were:

A) ~~*firstly* c~~Could twin electrode (fixed-offset) and electrical resistivity imaging surveys still successfully locate both simulated clandestine burials beyond three years after burial? And if so, how long were they geophysically detectable for?

B) ~~*Secondly*~~ Could single profile GPR surveys successfully locate both simulated clandestine burials throughout the four to six year post-burial monitoring period? If this was the case, which dominant frequency antenna was optimal to detect them?

C) ~~*Thirdly*~~ When was the optimal time (both up to six years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey?

~~*A)*~~*D)* ~~*Finally,*~~ *W*hen should a forensic geophysical survey be undertaken in a six year search scenario?

Methodology

Study site

The chosen controlled test site was located on Keele University campus, ~ 200 m above sea level, close to the town of Newcastle-under-Lyme in Staffordshire, UK. The local climate is temperate, which is typical for the UK [49]. The study site was a grassed, small rectangular area (~25 m x ~25 m), surrounded by small deciduous trees (Fig. 1). The geophysical survey area measured 5 m x 14 m and sloped by approximately 3º from northwest to southeast. Within this area were the 'naked pig' grave, the empty grave and the 'wrapped pig' grave emplaced in sandy loam soil (Fig. 1). [47] provides other relevant background site information.

The test site was located ~200 m from the Keele University weather observation station, which continually measured daily rainfall and air and ground temperatures as well as having soil temperature probes at 0.1 m, 0.3 m and 1.0 m below ground level. Figure 2 shows a monthly summary of the total rainfall and average temperature data over the monitoring period with temperature data for the zero to three year monitoring study also shown for comparison. The local weather station data showed that total monthly rainfall during the four to six year study period ranged from 2.6 mm to 152.2 mm, with an overall monthly average of 64.7 mm, the same as for the zero to three year monitoring period [47]. Average monthly air temperatures ranged from -1.2 ºC to 12.8 ºC, with an overall monthly average of 5.5 ºC, 3.2 ºC colder than for the zero to three year monitoring period (Fig. 2). However, note at 0.3m bgl the average temperature was 10.2 ºC for the ~~three~~ four to six year monitoring period and 9.8 ºC for the 0-3 year monitoring period [47]. Accumulated Degree Day (ADD) data (see [50] for background) detailed in Table 1 quantified these temperature differences.~~All four to six year monitoring period weather statistics were broadly similar when compared to the 0-3 year monitoring period (see [47]), including below-ground temperatures, although surface temperatures were, on average, 2 °C relatively colder for the four to six year monitoring period (Fig. 2).~~

FIG. 1. -position

FIG. 2. -position

Simulated graves

Five simulated graves were created at the site (Fig. 1A). Three of the graves were used for the repeat geophysical surveys, whilst ground water samples were collected at regular intervals from both the fourth grave and a separate control site situated ~10 m upslope away from the graves (Fig. 1E-F), both of the soilwater sampling sites being outside the geophysical survey area (Fig. 1A). Of the three simulated graves geophysically surveyed, one contained a naked pig carcass, one contained a ~~wrapped~~ carcass wrapped in woven PVC tarpaulin and the third was an empty grave to act as a control (Fig. 1). Pig cadavers are commonly used in such monitoring experiments as they comprise similar chemical compositions, size, tissue:body fat ratios and skin/hair type to humans [51,52]. The grave emplacement procedure was described in [47].

Bulk ground water conductivity data collection

Ground water sample lysimeters were emplaced both within a grave containing a pig carcass outside the geophysical survey area and a further lysimeter ~10 m from the survey area to act as control (Fig. 1). The lysimeter emplacement and regular sample collection (Table 1) and analysis procedures used in this study were the same as for the initial three year monitoring period and are described in [47]. The only change was the sample frequency with samples collected at approximately three-monthly seasonal intervals during the four to six year monitoring period due to limited monthly changes observed in the zero to three year monitoring period [47] and survey time constraints (Table 1).

TABLE 1.

Near surface geophysical data collection & processing

~~Fixed-offset~~ Twin electrode (0.5 m fixed-offset) resistivity surveys were conducted at three monthly intervals over the geophysical survey area (Fig. 1A-B) during the four to six year monitoring period (Table 1). Data was collect~~ion~~ed using the RM15 (Geoscan™ Research) resistivity meter on a 0.25 m by 0.25 m grid with remote probes placed on the same position 17 m from the survey area for consistency. ~~and~~ ~~s~~Subsequent data processing methodology was the same as detailed in [47].

A 2D Electrical Resistivity Imaging (ERI) survey line orientated SW-NE (Fig. 1A-B) was surveyed at approximately three-monthly intervals (Table 1). 32 electrodes were placed every 0.5 m along ~~T~~the 15.5 m long survey profile ~~was 15.5 m long and~~that bisected all three graves (Fig. 1A). Geophysical survey collection using a Campus™ TIGRE system and subsequent inversion using Geotomo™ Res2Dinv v.355 software used in this study were the same as for the initial three year monitoring period and are described in [47].

Due to the variable results of horizontal time slices that GPR data generated in the zero to three year monitoring survey period (see [47]), 2D GPR profiles were only collected on two profiles within the survey area that bisected the two simulated graves with pigs present (Fig. 1A) at approximately three-monthly intervals (Table 1). GPR data collection using the PulseEKKO™ 1000 equipment utilised 110 MHz, 225 MHz, 450 MHz and 900 MHz dominant frequency antennae, with radar trace spacings being 0.2 m, 0.1 m, 0.05 m, and 0.025 m, respectively, using 32 ‘‘stacks’’ to increase the signal-to-noise ratio and for all data sets for consistency purposes. ~~and s~~Subsequent data processing were the same as for the initial three year monitoring period and are described in [47]~~, except for migration and the horizontal time slices not being generated~~.

Results

Table 1 qualitatively summarises the respective geophysical anomaly visibilities in survey results based on [42] methodology of: *None, Poor, Good* and *Excellent.* A score of *None* indicated the respective grave was not detected, with a score of *Poor* showed a slightly discernible geophysical anomaly at the grave location. A score of *Good* demonstrates a clear geophysical anomaly that would be discernible in the field during a geophysical survey and a score of Excellent demonstrates a clearly discernible and prominent anomaly at the grave location.

Bulk ground water conductivity

Background soilwater conductivity measurements demonstrated that background values were consistent over the three year monitoring period (averaging 355 ± 0.1 μS/cm with 40 SD) that was comparable to the zero to three year monitoring period (averaging 444 ± 0.1 μS/cm). However, the pig leachate conductivity continued to reduce during year four (Fig. 3A), varying from 6,670 ± 0.1 μS/cm (1,099 days after burial) down to consistent and comparable background values of 356 ± 0.1 μS/cm after 1,670 days of burial to the end of the monitoring period. Pig leachate conductivity changes during the first three years of burial are reported in [47]. Leachate values in this study could be grouped divided into two clear linear groupings regressions of conductivity against post-burial days; 840-1,670 burial days (which included some data from the third year of monitoring) and 1,670 burial days to the end of the survey period respectively (Fig. 3A). The first data grouping had a decreasing regression line against burial days had with a reasonable fit ($R^2 = 0.88$),

~~but~~ with the ~~correlation for the~~ second data grouping having a flat regression line, albeit with a relatively poor correlation (R^2 = 0.47) due to its flat nature, evidencing that pig leachate conductivity was consistently at background soilwater values ~~line was much lower (R^2 = 0.48), see~~(Fig. 3A).

FIG. 3. - position

Site temperature variation could be removed from raw conductivity values as discussed in [47 Pringle et al. 2012 jfs] by weighting each day by its average daily temperature and then giving each day after burial an accumulated degree day (ADD) following standard methods [50]. This study still had the advantage of having temperature probe measurement data available from the actual mid-cadaver depth (~0.3m bgl) from the nearby meteorological weather station, instead of using average air temperatures (Fig. 2). This again allowed the ~~generation~~ separation of two data groupings with two linear regression correlations to be generated of conductivity against ADD, with similar fits to those generated against post-burial days (R^2 values of 0.86 and 0.57 respectively), see Fig. 3B.

Twin electrode ~~*Bulk ground*~~ *(fixed-offset) resistivity*

Bulk ground resistivity surveys acquired over the four to six year monitoring study period were again remarkably consistent, with average fixed-offset survey resistance values of 63.6 Ω (with 47.0 Ω minimum and 99.4 Ω maximum values respectively) (compared to an average of 67.1 Ω for zero to three years), after~~once~~ de-spiking data ~~processing had been undertaken~~ (only averaged 1.6 anomalous ‘spike’ per survey).

The three monthly processed fixed-offset resistivity surveys are graphically shown in Figure 4 (see Fig. 1A for ‘grave’ locations) and summarised in Table 1.

As found in the zero to three year monitoring datasets, the empty grave which acted as control could not be geophysically detected throughout the survey period (green boxes in Fig. 4). The naked pig grave (red boxes in Fig. 4) was anomalously temporally variable throughout the four to six year monitoring period, mostly comprising a small (<0.6 m^2 SD) amplitude mixed low/high anomaly, when compared to background values (Fig. 4 and Table 1). It only comprised a large ~~low~~ anomaly with a low resistivity (coloured blue) in the winter Year 4 dataset that was consistently observed in the zero to three year monitoring datasets (see [40] and Table 1). In contrast, t~~T~~he wrapped pig grave (blue boxes in Fig. 4) showed predominantly a large (>0.6 m^2 SD) amplitude high resistivity anomaly (coloured red/white), when compared to background values, that was mostly *Good* to *Excellent* rating and appeared to have increased in size from the zero to three year monitoring dataset immediately after burial (see [47] and Table 1).

FIG. 4. – position

Electrical resistivity imaging (ERI)

After de-spiking data, e~~E~~lectrical resistivity imaging surveys acquired over the four to six year monitoring study period were also again consistent, with average ERI six ‘n’ level survey resistivity values of 197.0 Ω.m with 106.0 Ω.m minimum and 318.9 Ω.m maximum respectively (compared to an average of 161.8 Ω for zero to three years)~~, once de-spiking data processing had been undertaken.~~ A summary of the 2D ERI profiles collected is graphically shown in Figure 5 (see Fig. 1A for profile location) and summarised in Table 1. An average inversion model error (RMS) of 2.1 (with 1.2 minimum and 5.1 maximum) after five iterations again indicated a very good model inversion fit to the collected resistivity values (compared to a RMS of 2.82 for zero to three years),.

The empty grave (marked in Fig. 5) again could be detected throughout the survey period, although, in contrast to the zero to three year monitoring period, it had consistently higher resistivity values, when compared to neighbouring regions (Fig. 5). The naked pig grave was again generally detectable as a consistent *Good* rated anomalous low, when compared to background values up to the end of year five, although thereafter it was difficult to resolve from neighbouring regions (Fig. 5 and Table 1). The wrapped pig grave was ~~mostly~~ surprisingly detectable as a large high *Good* rated resistivity anomaly, when compared to background values, although the anomaly ~~it~~ was relatively smaller in the summer and autumn of year's four and five (Fig. 5). In the zero to three year monitoring survey the high resistivity anomaly was relatively smallert ~~was a relatively small high resistivity anomaly in the zero to three year monitoring survey period~~ (see [47] and Table 1).

FIG. 5. - position

Ground Penetrating Radar (GPR)

The 2D GPR profiles acquired throughout the four to six year monitoring survey period are shown in Figure 6A and 6B (see Fig. 1A for profile locations) and summarised in Table 1. The 110 MHz dominant frequency 2D profiles showed the wrapped pig grave could still be consistently and clearly identified by a strong *Good* to *Excellent* rated hyperbola throughout the survey period (except for year 5 summer), although there was a continual reduction in reflection amplitudes. This was in contrast to the naked pig grave which was either ~~barely to~~ not detectable or at best produced ~~as~~ a *Poor* rated hyperbola throughout the~~is~~ survey period (see Fig.6A and 6B and Table 1). There were no clear hyperbolae other than those associated with the target graves within these 2D profiles.

The 225 MHz dominant frequency 2D profiles still showed the wrapped pig grave could be clearly identified by an obvious *Good* to *Excellent* rated hyperbola throughout the four to six year monitoring survey period, although there was also a continual reduction in reflection amplitudes (see Fig.6A and 6B). The second, slightly deeper reflector that was first resolved after 15 months of burial within the wrapped pig grave (see [47]) was still present in this dataset. The naked pig grave was ~~difficult~~ given a *Poor* to *None* rating of ~~to detect as a~~ hyperbola anomaly throughout the four to six year monitoring survey period although it was possible to~~just~~ detect~~able~~ in the autumn and winter data of year 4 (Fig. 6A/B). As per the zero to three year monitoring survey results [47], there were other, smaller hyperbolae present in the naked pig profiles that were not associated with the target. This ~~s which~~ would have made it difficult to identify the target grave if the position was not known. However, note they may have been detected if data were collected orthogonally to the primary survey line orientation or indeed if time slices were generated (although the zero to three year survey time slice data detailed in [47] was poor).

The 450 MHz dominant frequency 2D profiles showed the wrapped pig grave could be identified by a *Good* to *Excellent* rated hyperbola throughout the four to six year monitoring survey period, but this had a consistently low amplitude (see Fig.6A and 6B and Table 1). The second, slightly deeper hyperbola observed after 3 months of burial was still present during this survey period. The naked pig grave was rated as ~~poorly~~ *Poor to None rated* detectable as a hyperbola throughout the four to six year monitoring period. There were again numerous other, smaller hyperbolae present in both profiles that were not associated with the target grave which would have made it difficult to identify the target grave if the position was not known. These may, again have been detected if data were collected orthogonally to the primary survey line orientation or indeed if time slices were generated (although the zero to three year survey time slice data detailed in [47] was again poor).

The 900 MHz dominant frequency 2D profiles was rated *Poor* to *None* rated so was difficult to ~~could not~~ identify the naked pig grave throughout the four to six year monitoring period (see Fig.6A and 6B). There were numerous other, smaller hyperbolae present which would also have made it difficult to locate the target grave, although orthogonal surveys may have been successful.

FIG. 6(A).

FIG. 6(B).

Discussion

This study is the first published research to systematically detail resistivity, GPR and site monitoring data over a simulated clandestine grave test site over six years of burial summarised in Table 1. Importantly both naked and wrapped cadavers have been emplaced and surveyed which provides the two main burial styles encountered in discovered clandestine graves of murder victims. This has allowed questions by forensic search teams listed in the introduction to be answered that has not been able to be undertaken to date. These will be sequentially discussed and are deliberately similar to those posed in the zero to three year monitoring paper [47].

~~Firstly,~~ A) ~~c~~Could twin electrode (fixed-offset) and electrical resistivity imaging surveys still successfully locate the 'naked' and 'wrapped' simulated clandestine burials beyond three years after burial? And if so, how long were they geophysically detectable for? From the results of this long-term study, the answer was, it still depends on the burial style. The fixed-offset electrical resistivity surveys showed that a naked cadaver(s) has a good chance of being located up to 2.5 years after burial (see Table 1 and [47]), due to the highly conductive grave fluid' producing a consistent low resistance geophysical anomaly when compared to background site resistance values (Fig. 3). This agrees with other resistivity studies over simulated clandestine burials with similar monitoring time periods (see [26,52]. Recent collaborative research comparing the same monitoring experiment on three different University sites in contrasting soil types has evidenced that conductivity measurements of grave fluids could date the burial interval of a discovered clandestine grave in the field if a conductivity meter was available and enough grave fluid was present (see [45]).

However, this study showed that a naked cadaver would be very difficult to detect using fixed-offset electrical resistivity surveys after only four years of burial (Fig. 4) and using ERI surveys after five years of burial (Fig. 5) respectively. The majority of the grave fluids (other than that held by capillary pressure) would migrate away from the cadaver and potentially result in a geophysical anomaly not being over the target, and hence the subsequent search excavation team not finding the target, which would be especially problematic in surveys within significant topographic variation (see [1,30]. In contrast, the wrapped or clothed cadaver(s) essentially largely isolated the target and its conductive grave fluids from the surrounding soil, giving a potential barrier to electrical current. There was therefore a small and temporally varying high resistance anomaly, with respect to background site resistance values, identified over the wrapped target location in the zero to three year monitoring data (see [47]), the varying nature suggested to be caused by some leaking of grave fluids into the surrounding soil. However, this paper detailing the four to six year monitoring data showed a consistent large high resistance anomaly, when compared to background site resistance values, to be present in both the fixed-offset and ERI electrical resistivity datasets over the wrapped cadaver (see Figs. 4 and 5), this consistency presumably due to most grave fluid at this time period being largely absent from the survey area. Note that wrapping a body in plastic or clothing has also been reported by others to slow decomposition [53] and inhibit micro-organism activity [51] which therefore suggests a clandestinely buried body may be identifiable for longer if wrapped in woven PVC tarpaulin as compared to naked.

Using all the resistivity datasets collected in the six year monitoring period, a graphical time-line diagram has been generated to show temporal resistivity anomaly variations (Fig. 7). In terms of optimally configuring fixed-offset resistivity equipment if the likely depth of burial is unknown, modern versions (eg. the Geoscan™ RM-15 used in this study) have the capability to collect and digitally record fixed-offset resistivity data at a variety of probe spacings almost simultaneously at each sampling position (see [54] for forensic resistivity dataset examples). This would therefore not significantly add to survey time if more than one probe spacing data is collected and trace sample spacing could still be comparatively small so that any potential loss in resolution is minimised. The forensic resistivity su\~~r~~vey results in this paper are in sandy loam soil, with good forensic resistivity survey results also reported in coastal sand [36], chalky [26] and black earth [54] soil types respectively, but relatively poor results in coarse pebble soil types [54].

FIG. 7. - position

~~Secondly,~~B) ~~c~~Could single profile GPR surveys successfully locate both simulated clandestine burials throughout the four to six year monitoring period? And which dominant frequency antenna was optimal to detect them? From the results shown in this four to six year monitoring study, the naked cadaver was not able to be detected on 2D GPR transverse profiles using either the 110 MHz or 900 MHz dominant frequency antennae and was only poorly detectable by the 225 MHz dominant frequency antennae in the autumn to winter datasets (Fig. 6A/B). This was in contrast to the zero to three year monitoring period [47] and other studies undertaken on [47] timescale (e.g. see [38,39,42]). The naked cadaver, however, was detectable as a deeper ½ hyperbolic reflection event in the 450 MHz 2D transverse profiles although this did not have high amplitudes (Fig. 6A/B). In contrast, the wrapped cadaver was

detectable on 2D GPR profiles using all the frequencies trialled, namely the 110, 225 and 450 MHz dominant frequency antennae (the 900 MHz antennae was not used over this grave, but it is believed that the grave could have been detected with this frequency based on the other frequency data). This was presumably still due to the wrapping surface allowing stronger GPR reflections to be obtained, with the decomposing naked cadaver attenuating a greater proportion of the GPR signal as other authors have noted (e.g. see [42]). This radar absorption would be exacerbated by the pig-chest cavity having collapsed during decomposition stages as noted in [47], which is a probable explanation for the two GPR hyperbolae still present in 225 and 450 MHz dominant frequency data over the target location (Fig. 6A/B). 225 MHz dominant frequency antennae was shown in this study to be preferable to the other frequencies trialled (110, 450 and 900 MHz frequencies) in the 2D profiles due to a detectable anomaly, target resolution and fewer non-target hyperbolae present in the relative higher frequency data; note also forensic 225 MHz frequency radar surveys also took less time in the field to acquire when compared to their higher frequency versions. This could be an important factor for a forensic search team to consider if the proposed area is significant in size or if manpower and/or budget are limited. This agrees with others (e.g. [42]) who also suggested that 2D GPR profiles should be collected in both orientations over a survey site if possible to have the best chance of detection.

C) ~~Thirdly, w~~When was the optimal time (both up to six years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey? Clearly from the results shown in this study and others (e.g. [42]) the burial style is key, it would be difficult to detect a naked burial after the first 18 months of burial using the resistivity and GPR survey methods detailed here and in [47]. However, note that other studies have shown favourable GPR survey results over much older burials in different ground conditions (eg. ([3,34,54,55]). Using [37 Schultz & Martin 2012] four-fold method for qualitatively determining a hyperbola anomaly response over a simulated burial, i.e. excellent, good, poor and none, Figure 8 graphically summarises this for the (A) wrapped and (B) naked cadaver respectively. Whilst there is a general reduction in hyperbola quality in both burial styles, with the naked cadaver being much more difficult to detect, there is a seasonal effect, with autumn and winter surveys, especially in years four to six post burial, generally better at resolving the targets. This has also been observed by authors geophysically monitoring simulated clandestine burials on shorter time scales (e.g. [42]).

The resistivity surveys also showed a similar pattern, especially the fixed-offset electrical resistivity surveys which, when following [46] methodology to numerically measure resistivity anomaly relative areas over time, consistently showed winter surveys were optimal (Fig. 9Table 1). Each autumn to winter the anomalies over both the naked and wrapped cadavers increased in area and reduced in normalised standard deviation (SD) values whereas they were comparably smaller and had larger SD values in the summer months (Fig. 8). The naked cadaver's anomaly and the normalised SD of the datasets got progressively smaller over time, but the wrapped cadaver's relatively high resistance anomaly increased in size over the six year study period (Fig. 8). Temporally varying resistivity anomalies over fixed archaeological targets have also been reported by [56] who undertook time-lapse resistivity surveys over UK Roman fortification defence ditches. This study therefore shows the cyclical nature of low winter/spring SD values and high summer/autumn SD values repeating each year that was most probably due to the soil having reduced moisture content during the warmer and dryer periods but, importantly, in a non-uniform manner for this study site. Thus the 'noise' present within the geophysical data significantly increased during these seasonal periods and effectively 'masked' the target(s). See ([52] and [57] for detailed analysis of site soil moisture for the first two years of burial.

FIG. 8. - position

D) ~~Finally, w~~When should a forensic geophysical survey be undertaken in a six year search scenario? From this and other studiesy (e.g. 38-42,44]), clearly the burial style is still key; although the wrapped grave was initially harder to detect with electrical resistivity surveys (as shown in [47]), in this paper it is relatively easier to detect after four to six years of burial (Fig. 7). The wrapping also makes the target easier to find with GPR as the wrapping makes a good reflective target (Table 1). So although wrapping may help to conceal a body in some ways (for example, it may trap scent and prevent decompositional fluids leaching into the soil), it may also make a body easier to find geophysically. If the burial style is not known, then it is suggested that both electrical and GPR surveys be undertaken to have the best chance of successful detection. Note a naked cadaver would be progressively more difficult to find after 18 months of burial as shown in this (Table 1) and other studies (see [38-42,44]~~Figs. 8 and 9~~), and therefore other complementary methods should be trialled (e.g. search cadaver dogs).

This study also shows reinforces other research (see e.g. 38-42,44,56]) the importance of when a forensic geophysical survey should be conducted within the year, seasonality has shown to be surprisingly important, and, if operational time permits, then geophysical surveys should be undertaken in winter to have the best chance of target detection success. If a past forensic geophysical search was unsuccessful, perhaps the results should be reviewed in terms of seasonality and perhaps re-surveyed if the original survey season was unfavourable. If there is a time-restricted element to the forensic search, then the season of surveying should be undertaken and an appropriate alternative search method should be chosen if necessary.

From this long-term simulated grave monitoring study and comparing results from [24,27],29,38-42, 44,57-60], we still recommend that forensic geophysical surveys should be undertaken prior to other, more invasive search methods (e.g. metal detectors, soil/methane probes and cadaver dog probes). Any resulting soil disturbances from these surveys would lead to more false positives for the resulting geophysical surveys, as found during the [29] forensic resistivity search. Once anomalous geophysical areas within the survey area are identified, these should be prioritised and then subjected to more detailed scientific investigations, which includes geophysical surveys (e.g. 2D ERI profiles, higher frequency 2D/3D GPR surveys), cadaver dogs, invasive probing, etc. See [11] for other geoscience search methods and suggested phased investigative approaches.

Conclusions and further work

Geophysical long-term monitoring survey results over the simulated clandestine burials shown in this study and by others in different soil types should be used both to assist forensic search investigators to use the appropriate search technique and equipment configuration, and indeed as a reference to allow comparison of data collected by forensic search investigators looking for similar clandestine burials of murder victims.

A *buried 'naked' victim* within a clandestine burial, if shallowly buried, should be able to be located within the first 4 years of burial using ~~fixed-offset~~twin electrode electrical resistivity surveys. If the burial depth is unknown, the use of wider electrode separations in addition to the ~~standard~~ most frequently used 0.5 m spacing is recommended. Resistivity surveys are also recommended to be undertaken in clay-rich soils over GPR surveys due to the likelihood of highly conductive 'leachate' being retained in the surrounding soil and GPR experiencing poor penetration depths in these soil types. However after this time period a naked victim would become progressively more difficult to locate using electrical methods, with the majority of the decompositional fluids migrating away from the target, depending upon the soil type. However, ERI 2D profiles could potentially still locate naked victims up to five years of burial if sited over it. 110 – 225 MHz dominant frequency GPR surveys could detect ~~it~~ targets well up to 18 months of burial, then 225 MHz frequency poorly in winter months up to five years of burial due to decomposition, although skeletal material may still be imaged depending on target(s) depth and specific site conditions. If time and manpower availability permits then winter surveys should be undertaken.

A *buried 'wrapped' or clothed victim* within a clandestine burial, if shallowly buried, should be able to be located using both fixed-offset electrical resistivity and ERI 2D Profile surveys throughout the six year monitoring period; in fact in this study it became progressively easier to detect the wrapped cadaver as the burial period extended. Medium (225-450 MHz) dominant frequency GPR antennae were deemed optimal frequency for detection due to good target resolution as other authors have evidenced (e.g. [41-42]); less non-target anomalies and data acquisition speed, although 110 MHz and 450 MHz frequency antennae data also resolved the wrapped grave throughout the study period, most probably due to the 'wrapping' producing a good reflective contrast. If time and manpower availability permits then winter surveys should be undertaken.

This study site will be continued to be monitored annually to discover *at what time* period after burial will geophysical surveys not be able to determine the location of a clandestine burial. Organic, inorganic and other analytical measurements are currently being undertaken to examine what may be causing the variability in grave 'soilwater' conductivity after burial with preliminary results looking promising [61].

Further analysis of the geophysical data will also be undertaken; both to determine if there are diagnostic GPR signal spectra for clandestine burials versus background signals and to determine if both GPR and resistivity datasets can be simultaneously inverted numerically to quantify anomaly location(s), sizes and to quantitatively combine these two geophysical search techniques.

This experimental methodology should be repeated on similar time scale in other, contrasting soil types, in order to determine if soil type is a major factor in the ability of forensic geophysical surveys to successfully locate a clandestine burial. On a longer time scale, it is planned that the experiment will be repeated using human cadavers rather than pig analogues, as this may be an important variable to consider.

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References:

1. Harrison M, Donnelly LJ. Locating concealed homicide victims: developing the role of geoforensics. In: Ritz K, Dawson L, Miller D, editors. Criminal and Environmental Soil Forensics, Dordrecht: Springer, 2009;197–219.

2. Larson DO, Vass A A, Wise M. Advanced scientific methods and procedures in the forensic investigation of clandestine graves. J Contemp Crim Justice 27 2011;27:149–82.

3. Davenport GC. Remote sensing applications in forensic investigations. Hist Arch 2001;35:87–100.

4. Killam EW. The detection of human remains. Springfield: Charles C Thomas, 2004.

5. Dupras TL, Schultz JJ, Wheeler SM, Williams LJ. Forensic recovery of human remains: archaeological approaches. 2nd ed, Boca Raton, FL: CRC Press, 2011.

6. Rebmann A, David E, Sorg MH. Cadaver dog handbook: forensic training and tactics for the recovery of human remains. Boca Raton:CRC Press, 2000.

7. Lasseter A, Jacobi KP, Farley R, Hensel L. Cadaver dog and handler team capabilities in the recovery of buried human remains in the Southeastern United States. J For Sci 2003;48:1–5.

8. Pye K, Croft, DJ. Forensic Geoscience: Principles, Techniques and Applications. London: Geol Soc London Spec Pub 232, 2004.

9. Ruffell A, McKinley J. Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations. Earth Sci Rev 2005;69:235–47.

10. Ruffell A, McKinley J. Geoforensics. Chichester: Wiley, 2008.

11. Pringle JK, Ruffell A, Jervis JR, Donnelly L, McKinley J, Hansen J, Morgan R, Pirrie D, Harrison M. The use of geoscience methods for terrestrial forensic searches. Earth Sci Rev 2012a;114:108-23.

12. Davenport GC, Griffin TJ, Lindemann JW, Heimmer D. Geoscientists and law enforcement officers work together in Colorado. Geotimes 1990;35:13–5.

13. Brilis GM, Gerlach CL, van Waasbergen RJ. Remote sensing tools assist in environmental forensics. Part I. Digital tools—traditional methods. Env For 2000a;1:63–7.

14. Brilis GM, van Waasbergen RJ, Stokely PM, Gerlach CL. Remote sensing tools assist in environmental forensics. Part II. Digital tools. Env For 2000b;1:1–7.

15. Hunter J, Cox M. Forensic archaeology: advances in theory and practice. Abingdon: Routledge, 2005.

16. Dickinson DJ. The aerial use of an infrared camera in a police search for the body of a missing person in New Zealand. J For Sci Soc 1976;16:205–11.

17. Ruffell A, McKinley J. Forensic geomorphology. Geomorph 2014;206:14-22.

18. Owsley DW. Techniques for locating burials, with emphasis on the probe. J For Sci 1995;40;735–40.

19. Ruffell A. Burial location using cheap and reliable quantitative probe measurements. For Sci Int 2005a;151:207-11.

20. Hunter J, Simpson B, Sturdy Colls C, Forensic approaches to buried remains (essential forensic science). Chichester: Wiley, 2013.

21. Reynolds JM. An introduction to applied and environmental geophysics, 2nd ed, Chichester: Wiley-Blackwell, 2011.

22. Mellet JS. Location of human remains with ground penetrating radar. In: Hanninen, P, Autio S, editors. Proc~~eedings of the~~ Fourth Int~~ernational~~ Conf~~erence~~ on

~~Ground Penetrating Radar~~GPR, 1992 Jun 8-13; Rovaniemi, Geological Surv~~ey of~~ Finland Spec~~ial~~ Paper 16;359–65.

23. Calkin SF, Allen RP, Harriman MP. Buried in the basement – geophysics role in a forensic investigation. Proc~~eedings~~ of ~~the~~ symp~~osium on the~~ ~~application~~ Appl~~of~~ Geophys~~ies to~~ ~~engin~~Eng~~eering~~ ~~and~~ environ~~mental~~ problems; 1995, Denver: Env Eng Geophys Soc;397–403.

24. Nobes DC. The search for ‘‘Yvonne’’: a case example of the delineation of a grave using near-surface geophysical methods. J For Sci 2000;45:715–21.

25. Scott J, Hunter JR. Environmental influences on resistivity mapping for the location of clandestine graves. In: Pye K, Croft DJ, editors. Forensic Geoscience: Principles, Techniques and Applications. London: Geol Soc London Spec Pub 2004;232:33–8.

26. Cheetham P. Forensic geophysical survey. In: Hunter J, Cox M, editors. Forensic Archaeology: Advances in Theory and Practice, Abingdon: Routledge, 2005;62–95.

27. Ruffell A. Searching for the IRA “disappeared”: Ground Penetrating radar investigation of a churchyard burial site. J For Sci 2005;50:1430-5.

28. Schultz JJ. Using ground-penetrating radar to locate clandestine graves of homicide victims: forming forensic archaeology partnerships with law enforcement. Homicide Studies 2007;11:15-29.

29. Pringle JK, Jervis JR. Electrical resistivity survey to search for a recent clandestine burial of a homicide victim, UK. For Sci Int 2010;202(1-3):e1-7.

30. Novo A, Lorenzo H, Ria F, Solla M. 3D GPR in forensics: finding a clandestine grave in a mountainous environment. For Sci Int 2011;204:134-8.

31. Schultz JJ. The application of GPR for forensic grave detection. In: Dirkmaat DC, editors. A companion to forensic anthropology, Hoboken, NJ: Blackwell, 2012, p.85-100.

32. Ruffell A, Pringle JK, Forbes S. Search protocols for hidden forensic objects beneath floors and within walls. For Sci Int 2014;237:137-45.

33. France DL, Griffin TJ. Swanburg JG, Lindemann JW, Davenport GC, Trammell V. et al. A multidisciplinary approach to the detection of clandestine graves. J For Sci 1992;37:1445–58.

34. Strongman KB. Forensic applications of ground penetrating radar. In: Pilon J, editor. Ground Penetrating Radar, Ottawa: Geological Survey of Canada Paper 90-4, 1992;203–11.

35. Freeland RS, Miller ML, Yoder RE, Koppenjan SK. Forensic applications of FMCW and pulse radar. J Env Eng Geophys 2003;8:97–103.

36. Pringle JK, Holland C, Szkornik K, Harrison M. Establishing forensic search methodologies and geophysical surveying for the detection of clandestine graves in coastal beach environments. For Sci Int 2012;219:e29-e36.

37. Pringle JK, Wisniewski K, Giubertoni M, Cassidy NJ, Hansen JD, Linford NJ, Daniels RM. The use of magnetic susceptibility as a forensic search tool. For Sci Int 2015a;246:31-42.

38. Schultz JJ, Collins ME, Falsetti AB. Sequential monitoring of burials containing large pig cadavers using ground-penetrating radar. J For Sci 2006;51:607–16.

39. Schultz JJ. Sequential monitoring of burials containing small pig cadavers using ground-penetrating radar. J For Sci 2008;53:279–87.

40. Pringle JK, Jervis J, Cassella JP, Cassidy NJ. Time-lapse geophysical investigations over a simulated urban clandestine grave. J For Sci 2008;53:1405-17.

41. Schultz JJ, Martin MM. Controlled GPR grave research: Comparison of reflection profiles between 500 and 250 MHz antennae. For Sci Int 2011;209:64-9.

42. Schultz JJ, Martin MM. Monitoring controlled graves representing common burial scenarios with ground penetrating radar. J App Geophys 2012;83:74-89.

43. Schotmans EMJ, Fletcher JN, Denton J, Janaway RC, Wilson AS. Long-term effects of hydrated lime and quicklime on the decay of human remains using pig

cadavers as human body analogues: Field experiments. For Sci Int 2014a;238:141.e1-e13.

44. Molina CM, Pringle JK, Saumett M, Hernandez O. Preliminary results of sequential monitoring of simulated clandestine graves in Colombia, South America, using ground penetrating radar and botany. For Sci Int 2015;248:61-70.

45. Pringle JK, Cassella JP, Jervis JR, Williams A, Cross P, Cassidy NJ. Soilwater conductivity analysis to date and locate clandestine graves of homicide victims. J For Sci in press.

46. Jervis JR, Pringle JK. A study of the affect of seasonal climatic factors on the electrical resistivity response of three experimental graves. J App Geophys 2014;108:53-60.

47. Pringle JK, Jervis JR, Hansen JD, Cassidy NJ, Jones GM, Cassella JP. Geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 0-3 years. J For Sci 2012b;57:1467-86.

48. Manhein MH. Decomposition rates of deliberate burials: a case study of preservation. In: Haglund WD, Sorg MH, editors. Forensic taphonomy: the post-mortem fate of human remains, Boca Raton, FL: CRC, 1996;469–81.

49. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydro Earth Sys Sci 2007;11:1633–44.

50. Vass AA, Bass WM, Wolt JD, Foss JE, Ammons JT. Time since death determinations of human cadavers using soil solution. J For Sci 1992;37:1236–53.

51. Carter DO, Tibbett M. Cadaver decomposition and soil: processes. In: Tibbett M, Carter DO, editors. Soil Analysis in Forensic Taphonomy: Chemical and Biological Effects of Buried Human Remains. Boca Raton: CRC Press, 2009;29–52.

52. Jervis JR, Pringle JK, Tuckwell GT. Time-lapse resistivity surveys over simulated clandestine burials. For Sci Int 2009;192:7-13.

53. Rodriguez WC. Decomposition of buried and submerged bodies. In: Haglund WD, Sorg MH, editors. Forensic Taphonomy: The Postmortem Fate of Human Remains. Boca Raton: CRC Press, 1997;459–68.

54. Hansen JD, Pringle JK, Goodwin J. GPR and bulk ground resistivity surveys in graveyards: locating unmarked burials in contrasting soil types. For Sci Int 2014;237:e14-e29.

55. Bevan BW. The search for graves. Geophysics 1991;56:1310–9.

56. Clark AJ. Seeing beneath the soil: prospecting methods in archaeology, 2nd rev. ed. New York: Routledge, 1996.

57. Jervis JR. The detection of clandestine graves using electrical resistivity surveys: results from controlled experiments and a case study (PhD dissertation). Keele: Keele University, 2011.

58. Ellwood BB, Owsley DW, Ellwood SH, Mercado-Allinger PA. Search for the grave of the hanged Texas gunfighter, William Preston Longley. Hist Arch 1994;28:94-112.

59. Ruffell A, McCabe A, Donnelly C, Sloan B. Location and assessment of an historic (150-160 years old) mass grave using geographic and ground penetrating radar investigation, NW Ireland. J For Sci 2009;54:382-94.

60. Powell K. Detecting human remains using near-surface geophysical instruments. Expl Geophys 2004;35:88–92.

61. Blom G, Davidson A, Pringle J, Williams A, Lamont A, Cassella JP. Chemical markers for the detection of clandestine graves – development of a complimentary technique for forensic geophysics? Recent Work in Arch Geophys and For Geosci: Future Horizons Conf, Geol Soc London, 2-3 December, 2014.

FIGURE CAPTIONS:

FIG. 1. (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI 2D profile lines, lysimeter positions and UK location map all shown (inset). (B) Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and (F) soil fluid measurement photographs respectively. Modified from [47].

FIG. 2. Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the four to six year study period. Dashed average temperature line is for zero to three years survey period [47] shown for comparison.

FIG. 3. (A) Measured pig leachate (diamonds) and background (triangles) soil-water fluid conductivity values over the 6-year survey period; 4-6 years to the right of the vertical dotted line. (B) Measured soil-water conductivity versus accumulated degree day (ADD) plot produced from (A) by summing average daily 0.3 m bgl after burial temperatures (see text). Best-fit linear correlation formulae and confidence (R2) values are also shown. Modified from [47].

FIG. 4. Fixed-offset processed electrical resistivity datasets for the four to six year study period (year and season shown). Red, green and blue rectangles indicate positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).

FIG. 5. Individually inverted 2D Electrical Resistivity Imaging (ERI) Wenner array (0.5 m spaced electrode) profiles for the four to six year study period (year and season

shown); model inversion errors (RMS) for the fifth iterations are indicated. Positions of naked pig, empty and wrapped pig graves are also shown (dashed lines). See Fig. 1A (ERI/ERI') for location.

FIG. 6(A). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for ~~the four to six year study period~~ 39 – 54 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).

FIG. 6(B). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 57 – 72 post-burial months ~~the four to six year study period~~ (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).

FIG. 7. Summary qualitative analysis plot of resistivity data over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed lines (see key and text). Modified from [47].

~~**FIG. 8.** Summary qualitative analysis plots of GPR data collected over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed line (see key and text).~~

FIG. 8. Summary quantitative analysis plots of fixed-offset resistivity data collected over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed line. (A) Standard deviations (SD) for each survey, note

875 SD values are highest in late summer; residual volume analysis of (B) naked pig cadaver and (C) wrapped pig cadaver (see text). Modified from [46].

TABLE CAPTION:

TABLE 1. Summary of geophysical surveys and their respective geophysical anomalies ~~data collected detailed~~ in this ~~paper~~study (4-6 year results below horizontal line). [△]~~GPR surveys conducted the day after respective survey dates and groundwater conductivity measurements collected the day before respective survey dates.~~ [+]Burial date was 7th December 2007. *ADD date based on average daily site temperatures at 0.3 m bgl (see [47]).

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