Geophysical monitoring of simulated clandestine graves using electrical and Ground Penetrating Radar methods: 0-3 years after burial*

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ABSTRACT

This study provides forensic search teams with systematic geophysical monitoring data over simulated clandestine graves for comparison to active cases. Simulated 'wrapped' and 'naked' burials were created. Multi-geophysical surveys were collected over a three-year monitoring period. Bulk ground resistivity, Electrical Resistivity Imaging, multi-frequency Ground Penetrating Radar, grave and background 'soil water' conductivity data were collected. Resistivity surveys revealed the naked burial had consistently low-resistivity anomalies, whereas the wrapped burial had small, varying high-resistivity anomalies. GPR 110-900 MHz frequency surveys showed the wrapped burial could be detected throughout, with the 'naked' burial mostly resolved. 225 MHz frequency GPR data was optimal. 'Soil water' analyses showed rapidly increasing (year one), slowly increasing (year two) and decreasing (year three) conductivity values. Results suggest resistivity and GPR surveys should be collected if target 'wrapping' is unknown, with winter to spring surveys optimal. Resistivity surveys should be collected in clay-rich soils.

Keywords: forensic science; forensic geophysics; clandestine grave; monitoring; electrical resistivity; Ground Penetrating Radar; conductivity

Forensic investigators are increasingly using geoscientific methods to aid them in civil or criminal forensic investigations, predominantly to assist search teams or for trace evidence purposes (1-3). One key and high-profile ‘target’ for forensic search teams to detect and locate is human remains buried within clandestine graves (4-5). Whilst more traditional forensic search team methods include the use of remote sensing (6-7), trained victim recovery dogs (8), metal detectors (3), metal probes (9), geochemical surveys (3) and mass excavations (10), forensic geophysical surveys are starting to be utilised, albeit sporadically, in criminal search investigations (Harrison *pers. comm.*).

Geophysical surveys have been used to locate clandestine graves in a number of reported criminal search investigations (11-19). Geophysical surveys collected over simulated burials have been undertaken in order to collect control data (e.g. (20-22)). These studies have shown that the resulting geophysical responses could be reasonably 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. (16, 23-25), which have documented temporal changes in geophysical responses over their study periods. Uncertainties, however, 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 could be the temporal changes in grave soil characteristics, decomposition products, climatic variations and other site specific factors (see Fig. 1 and (26)).

This study was conducted to systematically assess the changing geophysical response of simulated clandestine graves during the first three years after burial. A clandestine grave is defined in this study as an unrecorded burial that has been hand-excavated and dug <1 m depth below ground level (bgl). There has been little published quantitative data on discovered clandestine burial dimensions, so a 0.5m bgl depth has been used, based on a 0.6 m depth bgl average from 87 discovered U.S. burials (28) and a 0.4 m depth bgl average from 29 discovered U.K. burials (10). It should be noted that geophysical results will vary depending upon the depth of burial and indeed on local soil type. The discovered graves published in (10,28) 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. Manhein (28) also detailed that almost ½ 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 a *naked* and *wrapped* burial, although it is emphasised that these obviously do not represent all types of potential style of burial.

There are many potential near-surface geophysical search techniques that could be utilised to search for clandestine graves (20,25,29). Electrical resistivity methods were selected since these have not been employed much to-date in active search cases but they have been shown to detect clandestine graves in different ground conditions (15,26,29-31). However geophysical responses will vary depending upon local soil type; therefore resistivity surveys will not be applicable in all searches. Ground Penetrating Radar (GPR) is the most frequently-used geophysical search technique (11,12,17,19,21), thus GPR datasets at the commonly-acquired (100-900 MHz) frequencies were also collected for comparison purposes. It was deemed unnecessary to also collect magnetic data, as, in contrast to historical graves which do show anomalies (32), magnetic results over simulated recent clandestine burials in a variety of depositional environments have proved to be unpromising for search teams (33).

The aims of this three 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 simultaneously collected in order to allow comparisons with other research studies and criminal search investigations. Basic forensic search questions which will be addressed by this study were: ***firstly*** could electrical resistivity fixed-offset surveys successfully locate both simulated clandestine burials? And if so, how long were they geophysically detectable for? ***Secondly*** could GPR surveys successfully locate both simulated clandestine burials throughout the three year monitoring period? And if so, how long were they geophysically detectable for? And finally, which dominant frequency antenna was optimal to detect them? ***Thirdly*** When was the optimal time (both up to three years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey? ***Fourthly,*** what advantages do 2D Electrical Resistivity Imaging (ERI) forensic surveys have over other electrical probe configurations or indeed other techniques? ***Fifthly,*** what effect does soil type have on a forensic geophysical survey being successful? ***Sixthly,*** what was important to do when processing electrical resistivity datasets? ***Seventhly***, what was important to do when processing GPR survey datasets? ***Finally,*** when should a forensic geophysical survey be undertaken in a 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 (34). The study site was a grassed, small rectangular area (~25 m x ~25 m), surrounded by small deciduous trees (Fig. 2). Therefore, this study site was representative of a semi-rural environment. Nearby borehole records showed that Carboniferous (Westphalian) Butterton Sandstone bedrock geology was present ~2.6 m bgl (35). Local soil maps, however, designated this area as made ground, due to the presence of demolished greenhouses. Initial soil sampling indicated a vertical site succession of a shallow (0.01 m) organic-rich, top soil (Munsell colour chart colour (Mccc): 5 YR/2/2.5), with underlying 'A' Horizon (Mccc: 5 YR/3/3) comprising predominantly of a natural sandy loam that contained ~5% of isolated brick and coal fragments. The natural ground 'B' Horizon was encountered at ~0.45 m bgl, dominated by sandstone fragments from the underlying bedrock.

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 bgl. This allowed below-ground site temperatures to be recorded. Figure 3 shows a monthly summary of the total rainfall and average temperature data over the monitoring period. Daily average temperatures at 0.3 m bgl were used to convert burial days to accumulated degree days (ADDs), which corrected for local site temperature variations by weighting each day by the average daily temperature and then giving each burial day an ADD value (36). Therefore, for a two-day period, in which the average temperature of the first day was 12 °C and the second day was 15 °C, the ADD value for those two days would be 27 ADD. The local weather station data showed that total monthly rainfall during the study period ranged from 21.6 mm to 166.7 mm, with an overall monthly average of 64.7 mm. Average monthly air temperatures ranged from -1.2 ºC to 15.8 ºC, with an overall monthly average of 8.7 ºC. Note at 0.3m bgl the average temperature was 9.8 ºC for the three year monitoring period.

Simulated graves

The Human Tissue Act (2004) prevents human cadavers from being used for research in the UK. Domestic pig (*Sus scrofa*) carcasses, sourced from a local abattoir, were instead used as proxies to simulate homicide victims, after the necessary permissions from the U.K.'s Department for Environment, Food and Rural Affairs (DEFRA) had been obtained. 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 (31,37). Five simulated graves were created at the site (Fig. 2A). 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 away from the graves (Fig. 2E-F), both of the water sampling sites being outside the geophysical survey area (Fig. 2A). Of the three simulated graves geophysically surveyed, one contained a naked pig carcass, one contained a wrapped carcass and the third was an empty grave to act as a control (Fig. 2).

The 'graves' were hand-excavated to 0.5 m bgl on the 7th December 2007. For each grave, the turf was removed and approximately 1.5 m long, 0.75 m wide and 0.6 m deep bgl pits were excavated. The three pig cadavers, which weighed ~80 kg each, were then placed in the graves (Fig. 2C/D). One pig cadaver was wrapped in a tarpaulin, which was made of woven polyethylene strands and measured 1.8 m x 2.7 m (product number: D00065, Duratool Corporation). The pigs had been deceased for less than 5 hours at the time of burial, having been dispatched by the abattoir by a bolt gun. The simulated graves were then backfilled to ground level with the excavated ground material and the 'graves' had the overlying grass sods carefully replaced (Fig. 2B), leaving a slight mound over the graves to account for later settlement. Leftover soil was disposed of away from the study site.

Bulk ground water conductivity data collection

Within the 'pig' lysimeter grave outside of the survey area (Fig. 2A), a ground water sample lysimeter was placed between the carcass and the grave wall (Fig. 2E and (27). The porous end cap of a model 1900 (SoilMoisture Equipment Corporation™) soilwater sample lysimeter was then vertically inserted into 'slurry' made up of a mixture of excavated soil and water, to ensure a good hydraulic conductivity between the ground and the lysimeter for future sample extractions (38). A control site lysimeter was also installed ~10 m from the survey area by digging a narrow hole (~0.3 m x ~0.3 m) to ~0.6 m depth bgl and the same procedure employed (Fig. 2A). Once installed, the exposed ends of the lysimeters were sealed with rubber stoppers. A hand vacuum pump was used to generate a suction pressure of 65 kPa within each lysimeter, in order for the instruments to draw fluid from the soil. Excavated ground material was then used as backfill and grass sods carefully replaced, following the same procedure as the survey graves.

Once the lysimeters were sited, plastic syringes with a tube attachment were used to extract ground water samples from both of the lysimeters two days before the bulk ground resistivity (fixed-offset) surveys were collected (Table 1). This would ensure measurements of groundwater would be from fluid collected within this time period, rather than from the last time the fluid was collected during the previous month. Prior to collection of the first groundwater samples, all lysimeters were emptied twice to remove the water used to make the slurry. The conductivity of all samples was measured and recorded in millisiemens per metre (mS m^{-1}) immediately after collection using a multiline P4 multi-parameter meter (WTW GmbH) (Fig. 2F). The data collection took ~0.5 h each time. See (27) for more information.

Bulk ground (fixed-offset) resistivity data collection & processing

A resistivity survey was conducted at the study site 11 days before burial for comparison with the post-burial data sets. Subsequent fixed-offset resistivity surveys were conducted at monthly intervals, commencing 28 days after burial (Table 1). The survey area measured 5 m x 14 m and sloped by approximately 3° from northwest to southeast. Within this area were the ‘naked pig’ grave, the empty grave and the ‘wrapped’ pig grave (Fig. 2). The twin probe array was chosen for this study, as this array has been proven to be capable of detecting clandestine graves (see (39)). Resistivity data were collected for the first year with an RM4 resistance meter (Geoscan™ Research) mounted on a custom-built frame that featured two 0.1 m long stainless steel electrodes. The mobile probes were separated by 0.5 m, whilst the remote probes were placed 1 m apart at a distance of 17 m from the survey area at the same position for each survey. The remote probes were inserted approximately 0.15 m into the ground. For each measurement, the mobile probes were pushed approximately 0.05 m into the ground. In every survey, parallel resistivity measurements were made at 0.25 m intervals along the SE-NW orientated, 5 m long survey lines that were 0.25 m apart (Fig. 2A). From years one onwards, a RM15 (Geoscan™ Research) resistivity meter was used, with the same equipment configuration and collection strategy as stated for the RM4. Both ends of each survey line were permanently marked with plastic pegs to ensure that the area surveyed remained constant. Two more pegs were used to permanently mark the reference probe locations. The RM15 surveys each took ~2 h to acquire.

Resistivity survey data were processed using the Generic Mapping Tools (GMT) software (40). To aid visual interpretation of the data, a minimum curvature gridding algorithm (41) was used to interpolate each dataset to a cell size of 0.125 m x 0.125 m. Long-wavelength trends were then removed from the data to allow smaller, grave-sized features to be more easily identified. Trend removal was achieved by fitting a cubic surface to the gridded data and then subtracting this surface from the data. Seasonal changes in site conditions, such as soil moisture content, caused variations in the range of resistivity values in datasets collected at different times of the year. Therefore, survey data were normalised by dividing each dataset by its standard deviation. All processed, normalised datasets then had a zero mean value and standard deviation units, which then made comparisons between different resistivity survey datasets possible.

Electrical resistivity imaging (ERI) data collection & processing

A 2D Electrical Resistivity Imaging (ERI) survey line orientated SW-NE (Fig. 2A-B) was permanently marked with plastic pegs and surveyed at approximately three-monthly intervals, starting at three months after burial (Table 1). The survey profile was 15.5 m long and bisected all three graves (Fig. 2A); with 32 x 0.3 m long stainless steel electrodes placed ~0.1 m into the ground every 0.5 m along the profile for each survey. There are no published papers of ERI profiles being used for forensic searches for clandestine burials, although ERI surveys have been used to evaluate the lateral and vertical extent of mass graves (42). ERI surveys are more commonly used (at this scale) for environmental forensic surveys (43). The 0.25 m electrode spacing was chosen because of the comparatively small spatial size of the target(s) and the requirement to cover all three ‘graves’ in the survey area using one 2D profile. For the first survey three months after burial, dipole-dipole, Schlumberger and Wenner array configurations were all collected, with the Wenner array configuration deemed optimal at this site. Therefore, Wenner array data were collected for all subsequent ERI surveys. These datasets were semi-automatically collected by a Campus™ TIGRE system using ImagerPro™ 2006 data acquisition software. Electrode contact resistances were checked before each profile was collected, and repositioned if necessary to gain equivalent contacts across each survey line, following standard practises (44). Ten 'n' levels were collected for each survey. Each electrode position was surveyed during the first survey using Leica™ 1200 differential GPS Real-Time Kinematic (RTK) equipment. The ERI surveys each took ~2 h to acquire.

Raw ERI data sets were then individually processed and inverted utilising a least-squares inversion approach using Geotomo™ Res2Dinv v.355 software in accordance with (45) resistivity surveying recommendations. The bottom four 'n' levels were removed and ½ cell spacing was utilised during the inversion process to remove potential edge effects and reduce any near-surface electrical resistivity variations respectively. The dGPS survey data were also integrated within profiles to show topographic corrections. Finalised models of true resistivity sections were lastly created.

Geotomo™ Res2Dinv software also allowed ERI analysis of temporal changes in resistivity by using a time-lapse inversion method. To avoid inverting models independently which can amplify data uncertainties (46), a least-squares smoothness inversion incorporating cross-model constraints (47) was utilised. A half cell spacing was also used to refine the model and reduce the impact of near surface effects (see (48)). In order to focus on the graves rather than seasonal resistivity variations of the whole profile, the resistivity data was constrained and compared to data from the first ERI survey of the graves, i.e. three months after burial. The resulting time-lapse profiles were therefore compared to the first survey and thus not independently inverted as was undertaken with the raw ERI data sets (45).

Electrical resistivity 2D profile models

Once the site monitoring data had been collected, simple 2D summary models of the survey site were then generated using Geotomo™ Res2DMod v.3.0 software. These aimed to improve the 2D resistivity model generated by (15) by using the site monitoring data for model calibration. Three models were generated to represent the site at years one, two and three after burial. Numerical cell dimensions were 32 cells across and 12 cells deep, to be similar to the ERI 2D profile data configuration. Model layers and targets were calibrated to the collected 1D soil profiles and measured grave dimensions, with apparent resistivities of the top cells calibrated to contemporary resistivity fixed-offset surveys. For the year 2 model, values were 0.35 Ω.m for the naked pig grave, 59 Ω.m for the empty grave and 63.1 Ω.m for the surrounding model top layer respectively. Deeper layer 2 cell values of 200 Ω.m and 500 Ω.m for the 'wrapped pig' grave were obtained from ERI surveys and 'grave soil' conductivity measurements. The computer programme also allowed synthetic ERI 2D profiles to be generated using the input information to calculate apparent resistivities. Wenner array ERI profiles were therefore inverted to be comparable to the actual Wenner array ERI profiles collected at the same time periods for comparison purposes.

Ground Penetrating Radar (GPR) data collection & processing

Repeat GPR survey datasets were also collected within the survey area (Fig. 2A) at approximately three-monthly intervals after burial (Table 1). There are numerous published papers of forensic GPR surveys for criminal (11,12,17,19) and simulated clandestine burials (23-25). Most published forensic case studies using GPR use medium (200-500 MHz) frequency antennae (e.g. (13,19,49). PulseEKKO™ 1000 equipment utilised 110 MHz, 225 MHz, 450 MHz and 900 MHz dominant frequency antennae to collect four datasets for each repeat survey post burial to investigate these commonly used frequencies and the less used ones. It was decided that 50 MHz and 1,200 MHz dominant frequency datasets would not be acquired as these would be too low resolution and take too long to acquire respectively to be used in forensic search cases effectively.

The 14 m x 5 m survey area was GPR surveyed on 0.5 m spaced, 5m long SE-NW orientated, parallel survey lines by 110 MHz, 225 MHz and 450 MHz dominant frequency antennae. Using 0.5 m spaced survey lines for the 450 MHz frequency datasets was due to time constraints – ideally 0.25 m spaced survey lines should be utilised for this frequency. The transmitter antennae always led each profile for consistency purposes. The 900 MHz dominant frequency antennae were used to acquire datasets on 0.25 m spaced lines over a smaller area, centred over the ‘naked pig’ grave (Fig. 3A). Radar trace spacings were 0.2 m, 0.1 m, 0.05 m and 0.025 m for the 110, 225, 450 and 900 MHz frequency data respectively, using 32 ‘stacks’ to increase the signal-to-noise ratio and for all datasets for consistency purposes. The GPR surveys took ~1 h, ~2.5 h, ~4 h and ~2 h to acquire for the 110, 225, 450 and 900 (subset) MHz dominant frequency datasets respectively.

Once the 2D GPR profiles for each dominant frequency antennae were acquired, they were downloaded and imported into REFLEX-Win™ v.3.0 processing software. For each 2D profile, the first arrival wavelets were first picked and shifted to ensure consistent arrival times at 0 ns. Processing steps were applied in order to filter out non-target 'noise' and therefore make the target hyperbolae more pronounced. These steps were: (1) subtracting the mean from traces ('dewowing'), (2) picking first arrivals and (3) applying static correction and moving the start times for traces in all profiles to 0 ns, (4) applying a 1D Butterworth bandpass filter to remove low-amplitude frequencies, (5) background-removal to reduce any 'ringing' effect and finally (6) applying a Stolt migration in accordance with the target hyperbolae velocities. Lastly horizontal time-slices of the four dominant frequencies datasets for each survey were generated using the processed 2D profiles within REFLEX-Win™ v.3.0 processing software. Time slices were generated by collapsing a ~6 ns (9 ns – 15 ns) time window containing the target hyperbolae to display absolute amplitude values.

Results

Bulk ground water conductivity

Background soilwater conductivity measurements demonstrated that background values were consistent over the three year survey period (averaging 444 ± 0.1 µS/cm with 84 SD), whereas the pig leachate conductivity varied throughout the survey period (Fig. 4A). Pig leachate conductivity varied from 729 ± 0.1 µS/cm (12 days after burial) up to a maximum of 33,400 ± 100 µS/cm (671 days after burial) over the survey period. Conductivity changes during the first two years of burial are reported in (8). The 'grave' conductivity values were twice the background values after only two weeks of burial. Leachate values could be grouped into five linear regressions; 0–150, 150–307, 307–671, 671-840 and 840-1,057 after burial days respectively (cf Fig. 4A). The final conductivity measurements at the end of the survey period could not be obtained due to prolonged cold conditions had frozen soilwater and thus prevented extractions (December 2010 had an average site monthly air temperature of -1.2 ºC). One, two and four regression lines had a good fit with the collected data (R^2 values of 0.97, 0.99 and 0.99 respectively), with the third and fifth regression lines demonstrating less confidence (R^2 values of 0.72 and 0.82 respectively), see Figure 4A. The second linear regression line represented the highest period of conductivity increase, increasing by ~144 μS/cm per day on average. This rapid increase in conductivity was most probably due to an increase in the rate of decomposition of the cadaver caused by higher soil temperatures in the spring and summer months (*cf.* Fig. 3). After 671 days of burial (~2 years), conductivity values rapidly decreased, ~136 μS/cm per day on average until 840 days after burial. From 840 days of burial to the end of the study period, the rate of conductivity decrease then slowed significantly; even during the summer months (*cf.* Fig. 4A).

Site temperature variation could be removed from raw conductivity values as previously discussed by weighting each day by its average daily temperature and then giving each day after burial an accumulated degree day (ADD) following standard methods (36). This study 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. 3). This allowed a reduction of one linear regression line to four regressions, with an improved correlation for the first 307 days of burial (R^2 value of 0.99), see Fig. 4B.

Bulk ground (fixed-offset) resistivity

Bulk ground resistivity surveys acquired over the study period were remarkably consistent, with average fixed-offset survey resistance values of 67.1 Ω (with 49.6 Ω minimum and 97.8 Ω maximum values respectively), once de-spiking data processing had been undertaken (only averaged one anomalous 'spike' per survey). Selected processed fixed-offset resistivity surveys are graphically shown in Figure 5 (see Fig. 2A for 'grave' locations). These shown datasets are acquired at three-monthly intervals, except the control dataset (acquired before grave emplacement) and a survey collected two weeks after burial (see Table 1 for full survey list). The control dataset showed the site was comparatively heterogeneous geophysically before burial, with significant areas of high resistivity at 0-2 m and 4.5-8 m on the X axis when compared to background areas. This is perhaps unfortunate for the experiment but a good test in identifying target 'graves' in a real environment.

The 'empty' grave which acted as control could not be geophysically detected throughout the survey period (green boxes in Fig. 5). The 'naked pig' grave (red boxes in Fig. 5) could predominantly be identified as a resistive low (coloured blue) anomaly, when compared to background values, that appeared four weeks after burial and generally became consistently larger in planview than the grave throughout the survey period, although there were variations in both amplitude strength and plan view area covered (*cf.* Fig. 5). The 'wrapped pig' grave (blue boxes in Fig. 5) showed predominantly a smaller high resistivity anomaly, when compared to background values, which appeared immediately after burial. Temporal variations were present, with no associated grave anomaly present at 196 days after burial and both low and high anomalies present at 700 days after burial.

Electrical resistivity imaging (ERI)

Electrical resistivity imaging surveys acquired over the study period were also consistent, with average ERI six ‘n’ level survey resistivity values of 161.8 Ω.m (with 137.6 Ω.m minimum and 206.0 Ω.m maximum respectively), once de-spiking data processing had been undertaken. A summary of the 2D ERI profiles collected is graphically shown in Figure 6 (see Fig. 2A for profile location and Table 1 for collection dates). An average inversion model error (RMS) of 2.82 (with 1.7 minimum and 5.5 maximum) indicated a very good model inversion fit to the collected resistivity values.

The ‘empty’ grave (marked in Fig. 6) could be detected throughout the survey period as it had consistently slightly lower resistivity values, when compared to neighbouring regions. The ‘naked pig’ grave was detectable throughout the survey period (albeit poorly at 23 months after burial – Fig. 6K), being a consistently anomalous low, when compared to background values. It also reached the largest size ~one year after burial (Fig 6D). The ‘wrapped pig’ grave was mostly detectable as a smaller high resistivity anomaly, when compared to background values, although it could not be detected in the 1 year and 18 months after burial profiles (Fig. 6D and 6H).

The time-lapse difference ERI profiles shown in Figure 7 show the percentage change in resistivity compared to the reference (March 2008) dataset. The time-lapse results reveal that up to 20 months post-burial (see Fig 7A – 7G) there is a consistent and significant (<30%) reduction in the resistivity of the soils within and surrounding the naked and wrapped pig cadavers. Spatially these decreases in resistivity are most prominent directly below the cadavers and exhibit a downward shift over time which is highly indicative of the fluid flow associated with decompositional leachate plumes. Interestingly the profile collected ~9 months after burial shows the 'empty' grave to have relative lower resistivity than the reference dataset (Fig. 7C), an observation that is not obvious in the fixed-offset data of the same time period (280 day labelled image in Fig. 5). Both this and the overall resistivity reduction of the near-surface soils seen in many of the time-lapse profiles could be attributed to tree-root related activity; during spring and summer, fine, highly conductive tree roots become active and grow (particularly in soil areas of reduced density/increased porosity such as that of the empty grave) to exploit surface water resources (50). Over time the accumulative drying effects of root absorption and those due to summer (i.e. increased evapotranspiration, reduced rainfall) are typically observed during autumn (Sep – Nov) with significant (<150%) increases in resistivity (46). It is important to note however that this is not clearly noticeable in the early post-burial stages (Fig 7B – 7G) and is only prominent in the later post-burial stages (Fig 7H – 7K). The other main observation from the time-lapse results is both the 'naked pig' and 'wrapped pig' graves have consistently increased resistivities from two years after burial onwards, when compared to the reference dataset (Fig. 7H - 7L). This reflects the drying of the initially fluid rich cadavers and may also reflect the higher resistivity associated with the skeletal remains of the cadavers (as detailed in Fig. 1D).

Electrical resistivity 2D profile models

For the one year burial model, the synthetically generated ERI profile did not look that comparable to its equivalent survey ERI profile, although the ‘naked pig’ grave anomaly did look similar, being a shallow and isolated, almost spherical low resistive area when compared to background values. The synthetic ‘wrapped pig’ grave was not resolved, which was the same as shown in the true ERI profile, although the ‘empty grave’ was not imaged on the synthetic profile but was in the true ERI profile. For the two year burial model (Fig. 8), the synthetically generated ERI profile looked more similar to its equivalent survey ERI profile (*cf.* Fig. 6H). The synthetic ‘naked pig’ grave anomaly looked very similar to the true ERI profile, being a shallow semi-spherical low resistivity anomaly and both the ‘empty grave’ and ‘wrapped pig’ grave targets were both not resolved in either profile. For the three year burial model, the synthetically generated ERI profile did not look that comparable to its equivalent survey ERI profile, similarly to the one year after burial dataset. The ‘naked pig’ grave anomaly again did look similar, being a shallow and isolated, almost spherical low resistive area when compared to background values.

Ground Penetrating Radar (GPR)

Key 2D GPR profiles acquired through the survey period are shown in Figure 9A and 9B (see Fig. 2A for profile locations). Pre-burial profiles (to act as control) are also shown, except for 900 MHz frequency data which did not have a control dataset acquired.

The 110 MHz dominant frequency 2D profiles showed the ‘wrapped pig’ grave could be consistently and clearly identified by a strong hyperbola throughout the survey period, although there was a continual reduction in reflection amplitudes. The ‘naked pig’ grave was detectable as a hyperbola up to 18 months after burial, but this had significantly lower amplitudes when compared to ‘wrapped pig’ grave hyperbolae (*cf.* Fig.9A and 9B). After 18 months of burial, however, it was difficult to detect a hyperbola over the ‘naked pig’ grave. There were no clear hyperbolae other than those associated with the target graves within these 2D profiles.

The 225 MHz dominant frequency 2D profiles showed the ‘wrapped pig’ grave could also be clearly identified by an obvious hyperbola throughout the survey period, although there was a continual reduction in reflection amplitudes that was noticeable after two years of burial (*cf.* Fig.9A and 9B). There was also a second, slightly deeper reflector that was first resolved after 15 months of burial within the ‘wrapped pig’ grave. The ‘naked pig’ grave was detectable as a hyperbola up to 15 months after burial, but this had significantly less amplitude when compared to the ‘wrapped pig’ grave hyperbolae at the same frequency. After 18 months after burial, it was difficult to detect an anomaly over the ‘naked pig’ grave. There were other, smaller hyperbolae present in the ‘naked pig’ profiles that were not associated with the targets. The other hyperbolae present in the profiles would have made it difficult to identify the target grave after 18 months of burial to the end of the survey period.

The 450 MHz dominant frequency 2D profiles showed the ‘wrapped pig’ grave could also be identified by a hyperbola throughout the survey period, with again a continual reduction in reflection amplitudes that was noticeable after 27 months of burial to the end of the survey period (*cf.* Fig.9A and 9B). There was also a second, slightly deeper hyperbola that was first resolved after 3 months of burial. The ‘naked pig’ grave was detectable as a hyperbola up to 12 months after burial, but this had significantly less amplitude when compared to ‘wrapped pig’ grave hyperbola. After 15 months after burial, it was difficult to detect an anomaly. There were again numerous other, smaller hyperbolae present in both profiles that were not associated with the target grave.

The 900 MHz dominant frequency 2D profiles could only identify the ‘naked pig’ grave from 9 to 12 months after burial; apart from these times after burial, the grave location could not be identified (*cf.* Fig.9A and 9B). There were numerous other, smaller hyperbolae present which would have made it difficult to locate the target grave.

The 110 MHz dominant frequency repeat survey time-slices generally showed good results (Fig. 10A). The control dataset did not show any anomalies at the target ‘grave’ positions, but did show two high amplitude anomalies at the NW border of the survey area which were mostly present in all subsequent 110 MHz dominant frequency datasets. High amplitude isolated radar anomalies, generally significantly larger than the ‘graves’ in planview, were generally present within the ‘naked pig’ and ‘wrapped pig’ target grave positions throughout the three year study period, except for the ‘naked pig’ position in the year 2 and 3 winter datasets. Generally the wrapped pig cadaver showed as a larger and higher amplitude anomaly than the naked pig cadaver (Fig. 10A). Radar anomalies were also present in the ‘empty grave’ position in most datasets. There were a number of radar anomalies also present within the datasets that were not associated with the target ‘grave positions, notably in the year 0 winter, year 1 spring and summer, year 2 and year 3 summer respective survey datasets (Fig. 10A).

The 225 MHz dominant frequency repeat survey time-slices generally showed variable results (Fig. 10B). The control dataset did not shows any anomalies at the target ‘grave’ positions, but did show one high amplitude anomaly at the NW border of the survey area which was present in all subsequent 225 MHz dominant frequency datasets. High amplitude isolated radar anomalies, slightly larger than the ‘graves’ in planview, were generally present within the ‘naked pig’ and ‘wrapped pig’ target grave positions throughout the three year study period, except for the ‘naked pig’ position in the year 2 and 3 autumn datasets. ‘Target’ anomalies generally lessened in spatial extent and amplitude strength after year 1. Generally the wrapped pig cadaver also showed as a larger and higher amplitude anomaly than the naked pig cadaver (Fig. 10B). Radar anomalies were not present in the ‘empty grave’ position, except for the year 2 winter dataset. There were a number of radar anomalies also present within the datasets that were not associated with the target ‘grave positions, especially from year 2 spring survey datasets onwards (Fig. 10B) which would make locating the ‘target graves’ in these datasets problematic.

The 450 MHz dominant frequency repeat survey time-slices generally showed variable results (Fig. 10C). The control dataset did not shows any anomalies at the target ‘grave’ positions, but did show one high amplitude anomaly at the SW border of the survey area which was mostly present in subsequent 225 MHz dominant frequency datasets. High amplitude isolated radar anomalies, smaller than the 'graves' in planview, were present within the 'naked pig' and 'wrapped pig' target grave positions throughout the three year study period. 'Target' anomalies were generally consistent in spatial extent and amplitude strength throughout the survey period. Generally the wrapped pig cadaver also showed as a larger and higher amplitude anomaly than the naked pig cadaver (Fig. 10C). Radar anomalies were not present in the 'empty grave' position. There were a number of radar anomalies also present within the datasets that were not associated with the target 'grave positions, present in the year 0 winter survey and especially from year 2 autumn survey datasets onwards (Fig. 10C) which would make locating the 'target graves' in these datasets problematic.

Discussion

This is the first published research to sequentially collect three years of resistivity, GPR and site monitoring data over a simulated clandestine grave test site, so has now allowed some basic questions by forensic search teams listed in the introduction to be answered that has not been able to be undertaken to-date.

Firstly, could electrical resistivity fixed-offset surveys successfully locate the 'naked' and 'wrapped' simulated clandestine burials? And if so, how long were they geophysically detectable for? From the results of this study, the answer was: it depends on the burial style. The fixed-offset resistivity surveys showed that a 'naked' cadaver(s) has a good chance of being located up to three years after burial, due to the highly conductive grave 'fluids' producing a low resistance geophysical anomaly when compared to background site resistance values (*cf.* Fig. 4). Indeed it has been suggested that conductivity measurements could even date the burial interval of a discovered clandestine grave in the field if a conductivity meter was available and enough grave 'leachate' was present (see (27)). There is, however, no guarantee that a low resistance anomaly would still be present over a naked target *ad infinitum*. However, from the results shown in this study, a 'wrapped' or clothed cadaver(s) would be much more difficult to successfully locate using resistivity methods, as the wrapping essentially isolates the target(s) and its conductive grave 'fluids' from the surrounding soil (*cf.* Fig. 8). This therefore gives a potential barrier to electrical current and produced a small high resistance anomaly to be identified over the target location in this study, although the anomaly did vary temporally (*cf.* Figs. 5 and 6). The wrapping used for the pig cadaver in this study was a loose weave tarpaulin and most probably allowed leakage of grave 'fluids' into the surrounding soil to create the resistive low anomaly ~196 days after burial (*cf.* Figs. 5 and 6). This wrapping would be likely to be representative of a 'clothed victim' as clothes would not prevent decompositional fluids from leaking into the surrounding soils over time. Note that wrapping a body in plastic or clothing has also been reported by others to slow decomposition (52) and inhibit micro-organism activity (37) which therefore suggests a clandestinely buried body may be identifiable for longer if wrapped as compared to naked. Using all the resistivity datasets collected in this study, a graphical time-line diagram has been generated to show temporal anomaly variations throughout the survey period (Fig. 11). Both the (16) and (31) resistivity study results have also been added for comparison purposes, although the seasonal timing of the (16) study has not been confirmed. This study therefore predominantly agrees with other published studies on forensic resistivity surveys in that a consistent low resistivity anomaly was present over the 'naked pig' grave, although this varies temporally in both plan-view size and relative amplitude compared to background values. 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. 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. However note that these and other named resistivity survey results are only in a few soil types – not all soil types may be conducive to undertake resistivity surveys.

Secondly, could GPR surveys successfully locate both simulated clandestine burials throughout the three year monitoring period? And if so, how long were they geophysically detectable for? And finally, which dominant frequency antenna was optimal to detect them? From the results shown in this study, it was possible to initially locate both the 'naked' and 'wrapped' cadavers on 2D GPR profiles using the frequencies trialled, namely the 110, 225, 450 and 900 MHz dominant frequency antennae (although not the 900 MHz antennae only collected data over the 'naked' cadaver). However after 18 months after burial, only the 'wrapped' cadaver was relatively easy to locate in the 2D profiles, interestingly being the inverse of the resistivity survey results which found the 'wrapped' cadaver to be harder to locate (Figs. 5 and 6). This was presumably 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. This radar absorption would be exacerbated by the pig-chest cavity collapsing during later decomposition stages (cf. Fig. 1C), which is a probable explanation for the two GPR hyperbolae present in 225 and 450 MHz dominant frequency data over the target location later on during the survey period (*cf.* Fig. 9). The potential size of the target(s) may also be a factor; (24) found small pig cadavers were difficult to locate after 23 months of burial. The lower GPR frequencies trialled (110 and 225 MHz frequencies) were shown in this study to be preferable to the higher frequencies (450 and 900 MHz frequencies) in the 2D profiles as there were less non-target hyperbolae present in the data and surveys also took less time in the field to acquire. 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. Note; (51) suggested that 2D GPR profiles should be collected in both orientations over a survey site if possible to have the best chance of detection. The horizontal time-slices for the frequencies trialled showed generally good results throughout, with the wrapped cadaver again being spatially larger in extend and had a higher radar signal amplitude when compared to the 'naked' cadaver, presumably due to the better reflective surface of the former as previously noted. However, the 225 and 450 MHz dominant frequency time-slices contained a number of non-target anomalies that would make it difficult for search teams to be confident in picking the grave locations from this data alone (*cf.* Fig. 9). Results from this study therefore suggest that both fixed-offset resistivity and GPR surveys should be undertaken in forensic search surveys if the style of burial (i.e. wrapping) is unknown.

Thirdly, when was the optimal time (both up to three years post-burial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey? From the results shown in this study, a GPR survey should be undertaken ideally within the first 18 months of burial, if the burial style was not known, i.e. if it was a 'naked' cadaver; the target(s) may be more difficult to locate after this time of burial (*cf.* Fig. 9). Note that other studies have shown favourable GPR survey results over much older burials in different ground conditions (eg. (14,21,29)). In this study, however, the time of year in which a GPR survey was undertaken did not seem to matter in the 2D profiles, although the horizontal time-slice data showed ‘target’ anomalies to have lower amplitudes in winter surveys that may be due to higher soil moisture contents. This was in contrast to the resistivity surveys, which were best collected during winter to mid-spring months over search areas to have the best chance to detect a clandestine burial using resistivity methods (*cf.* Figs. 5, 6 and 11). This has also been reported by (53) who undertook time-lapse resistivity surveys over UK Roman fortification defence ditches. This study can partly quantify the reasons for the preferred resistivity winter survey season by analysing the fixed-offset resistivity survey data which had the most (monthly) surveys collected during the survey period. Although the average resistivities of all the fixed-offset resistivity surveys were broadly similar (Fig. 12A), the respective survey standard deviations were much more variable (4.4 – 20.1 SD); with surveys having much higher standard deviations during the summer and autumn months when compared to the winter and spring months (marked in Fig. 12B). As clearly illustrated, the standard deviation variations are cyclical; with low winter/spring SD values and high summer/autumn SD values repeating each year during the three year survey period. This 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 (54) for detailed analysis of site soil moisture for the first year of burial). Interestingly, the ‘wrapped pig’ grave resistivity anomaly, which could not be resolved in most of the summer surveys, returned during the winter and spring surveys (see Figs. 5 and 6). There were two SD survey outliers acquired on days 280 and 672 post-burial (Fig. 12B) that did not fit the other dataset curves which, on comparison with weather data (Fig. 3), were probably due to local climate variations. Specifically high and low rainfall respectively was experienced during the times of these two outlier surveys that did not follow the trends of other years (*cf.* Fig. 12B).

Fourthly, what advantages do ERI surveys have over other electrical probe configurations or indeed other techniques? The ERI profiles were significantly slower to acquire than fixed-offset configuration electrical surveys; typically only three to four 2D profiles could be collected per survey day which cover significantly less ground. This therefore suggested that ERI surveys should not be used as a primary forensic geophysical survey over a search area, unless the area to be investigated was comparatively small. A recommendation by (55) and reinforced from this study is that an ERI forensic survey should be used as a follow-on survey after targeted areas have been pinpointed by a previous survey, e.g. by a fixed-offset resistivity and/or GPR geophysical survey. ERI profiles do have the advantage of penetrating much further below the ground surface than a typically 0.5m-probe spaced, fixed-offset resistivity survey which would therefore resolve deeper graves than the 0.5m bgl graves investigated in this study. Finally collecting multiple 2D ERI profiles would allow 3D datasets to be generated that could better locate and define grave positions as (42) showed using this technique on a mass grave search.

Fifthly, what effect does soil type have on a forensic geophysical survey being successful? This was more of a difficult question to answer. This study was undertaken on a study site with a sandy loam soil with an underlying shallow (>3 m bgl) sandy bedrock geology. In comparison, the (31) simulated forensic geophysical study was undertaken in a mixed sand/silt loam soil, with comparatively deep (>20 m bgl) bedrock geology and found that a 'naked' pig cadaver could not be electrically detected after 11 months of burial. Both studies used a 0.5 m bgl burial depth but the cadaver sizes were significantly different (~80 Kg versus ~31 Kg for this study and the (31) studies respectively). It is therefore difficult to conclusively state which soil type would be optimal for a forensic resistivity survey to be undertaken. Results from this study suggests that finer-textured (i.e. clay-rich) soils, which better retains grave 'fluids' rather than being dissipated, may show better results than electrical surveys undertaken in more sand-rich soils. The (23) GPR time-lapse simulated burial study also concludes that pig cadavers were more easy to locate in sandy rather than clay-rich soil types. Therefore it is suggested that resistivity surveys would be more favourable than GPR surveys in clay-rich soil study sites. However, the environment of deposition would also be a factor, for example (56) found decomposition rates varied significantly from cadavers in a coastal environment versus a rural field environment. Saline soil water, such as some soil types found in coastal foreshore environments, would also significantly attenuate radar signals and thus result in poor penetration depths of GPR surveys in this environment. An urban soil garden environment would also be likely to contain significant heterogeneous materials, such as found in the (31) study, which would make identifying anomalous area in GPR surveys in this environment problematic.

Sixthly, what was important to do when processing electrical resistivity datasets? From reviewing this study fixed-offset resistivity survey results, initial recommendations were to be careful when ‘de-spiking’ datasets to remove anomalous readings (which were usually due to poor electrode contact resistances); isolated readings could be reasonably removed but removing clustered anomalous readings could potentially remove values associated with target(s). In this study, an average of only one anomalous reading was removed per survey dataset (~0.0008% of the total), although field operators in this simulated burial study were not under any survey time restraints which active forensic search teams may be under. During resistivity data processing, the most important step found in this study was detrending datasets; otherwise site trends would potentially have masked the anomaly location(s). It is important to point out that detrending resistivity datasets would be particularly important to undertake on survey area boundaries. If these boundaries are also field or hedge boundaries, as was the case in this study and in the forensic searches detailed in (16) and (18), then these boundaries will commonly produce high resistivity values due to low soil moisture content as hedge/tree roots extract soil water. The resulting large resistivity variations between survey edge areas and the rest of the survey area would thus potentially mask anomaly location(s). For the ERI profiles, it was also important in this study to utilise cross-model constraints for the time-lapse inversion and implement a user defined (rather than default) linear scale for the percentage change in resistivity when displaying the differential images. This was needed to reduce data uncertainties/artefacts and to highlight the subtle changes associated with the graves; without the user defined scales moisture content variations throughout the study period would have dominated and made it difficult to compare the different datasets acquired. This was a similar methodology used by (46) in a three year ERI time-lapse study of tree-induced subsidence, where the clay-rich soils experienced seasonal related resistivity changes over several orders of magnitude. However, normalisation should not be needed for an active forensic geophysical search.

Seventhly, what was important to do when processing GPR survey datasets? Reviewing this simulated study results, clear hyperbola anomalies were present in the raw data 2D profiles that were acquired over the target 'graves' and thus limited processing was necessary to identify these locations (*cf.* Fig. 8). This was similar to those shown in (23-24,51). Horizontal time-slices were also generated of the 110, 225 and 450 MHz dominant antennae frequency datasets and the simulated burial locations were mostly present as isolated, high amplitude anomalies. However, there was also a significant number of isolated, high amplitude anomalies present in the respective datasets that were not associated with the targets; this would make locating the targets difficult using time-slice data alone. This was also found in the (19) forensic search in a mountainous environment and the (25) simulated study in an urban garden environment. Generating time-slices also takes significantly more processing time to do that may be difficult to undertake during a forensic active search but could be undertaken later if time permitted. However, if the survey site ground conditions were moderately to highly heterogeneous containing a variety of materials, then 2D profiles would be sufficient.

Finally, when should a forensic geophysical survey be undertaken in a search scenario? From this simulated study and comparing results from (13,17,18,30,49,54,55), we 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 would lead to more false positives for the resistivity surveys, as found during the (18) 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.

Conclusions and further work

Geophysical monitoring survey results over the simulated clandestine burials shown in this study should be used 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 using fixed-offset electrical resistivity surveys. If the burial depth is unknown, the use of wider electrode separations in addition to the standard 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. GPR surveys were also not optimal to detect target(s) if there is an advanced state of decomposition as may be experienced during significant burial times, although skeletal material would still be imaged depending on target(s) depth and specific site conditions. A *buried 'wrapped' or clothed victim* within a clandestine burial, if shallowly buried, should be able to be best located using medium (110-450 MHz) dominant frequency GPR antennae over resistivity surveys, due to the 'wrapping' producing a good reflective contrast. Fixed-offset and ERI forensic resistivity surveys should be undertaken during winter to spring seasons if time and manpower availability permits. It did not seem to matter which season GPR data should be collected in.

For forensic geophysical data processing, resistivity data should be carefully processed, with detrending undertaken if survey grid edges border vegetation or other significant different land-use types; otherwise results will be masked by soil moisture variations. GPR data should show target hyperbola(e) in raw 2D data profiles in ideal ground conditions, which has the advantage over resistivity surveys which need to be processed before being interpreted. However, in more heterogeneous ground, or where the time since burial is significant, i.e. over 18 months, then horizontal 'time-slices' could be generated to locate more subtle features that otherwise may be missed using 2D profile data interpretation alone. However, a variety of non-target anomalies may also be present in time-slices that may make locating forensic targets more problematic.

If the likely depth of burial is unknown, once potential location(s) have been identified, it is recommended that multiple 2D ERI Wenner array profiles be collected using 0.5 m probe spacings for a minimum of a 32 electrode array. This survey configuration will be likely to penetrate to 2 m bgl and have the best chance to successfully locate a clandestine isolated or mass grave burial.

This study site will be continued to be monitored to discover *at what time* period after burial will geophysical surveys not be able to determine the location of a clandestine burial and also when 'grave soil' conductivity values will either return to background levels or reach equilibrium. Extracted soil water samples from both the ‘pig’ lysimeter and background lysimeter were immediately frozen after conductivity was measured for subsequent chemical analysis; it is planned that organic, inorganic and other analytical measurements will be undertaken to examine what may be causing the variability in pig ‘leachate’ conductivity after burial. This area of study has already begun; (33) details analysis of six months of samples using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

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 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. As an example, researchers at the TRACES facility at the University of Central Lancashire in Preston, UK, are acquiring monthly conductivity measurements of a pig cadaver buried at the same burial depth (0.5 m bgl) in a peat soil to compare with this study results. 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. We are currently exploring this possibility with Anthropology Research Facility researchers at the University of Tennessee Knoxville, USA.

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FIGURE CAPTIONS:

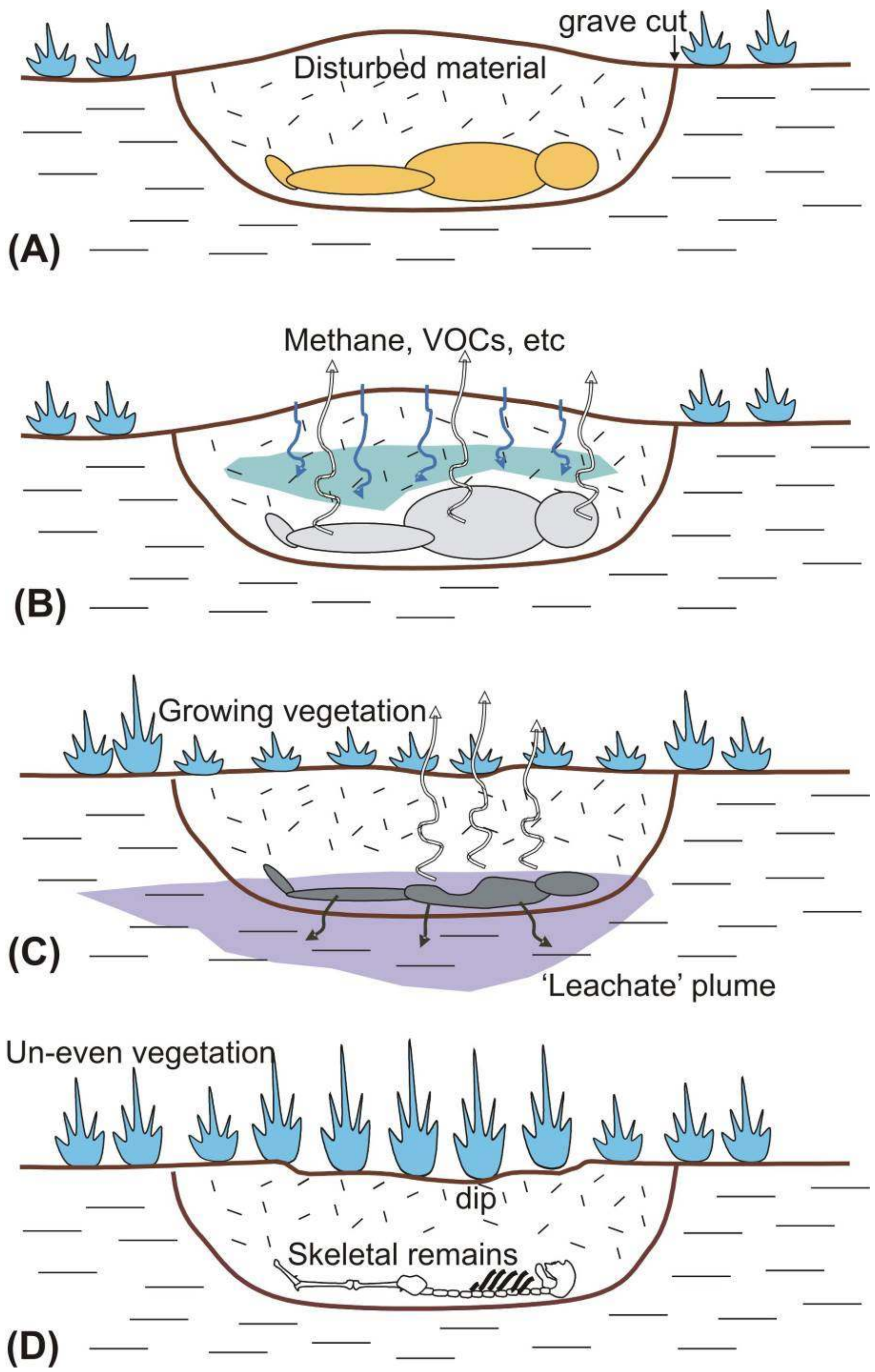

FIG. 1. Four likely sequential stages of clandestine burial. (A) Recent burial, surface expression is most obvious. (B) Early decomposition with cadaver dogs and/or methane probes being most useful. (C) Late-stage decomposition with conductive ‘leachate’ plume that should be resolved by electrical methods. (D) Final decomposition state that is arguably the most difficult to detect.

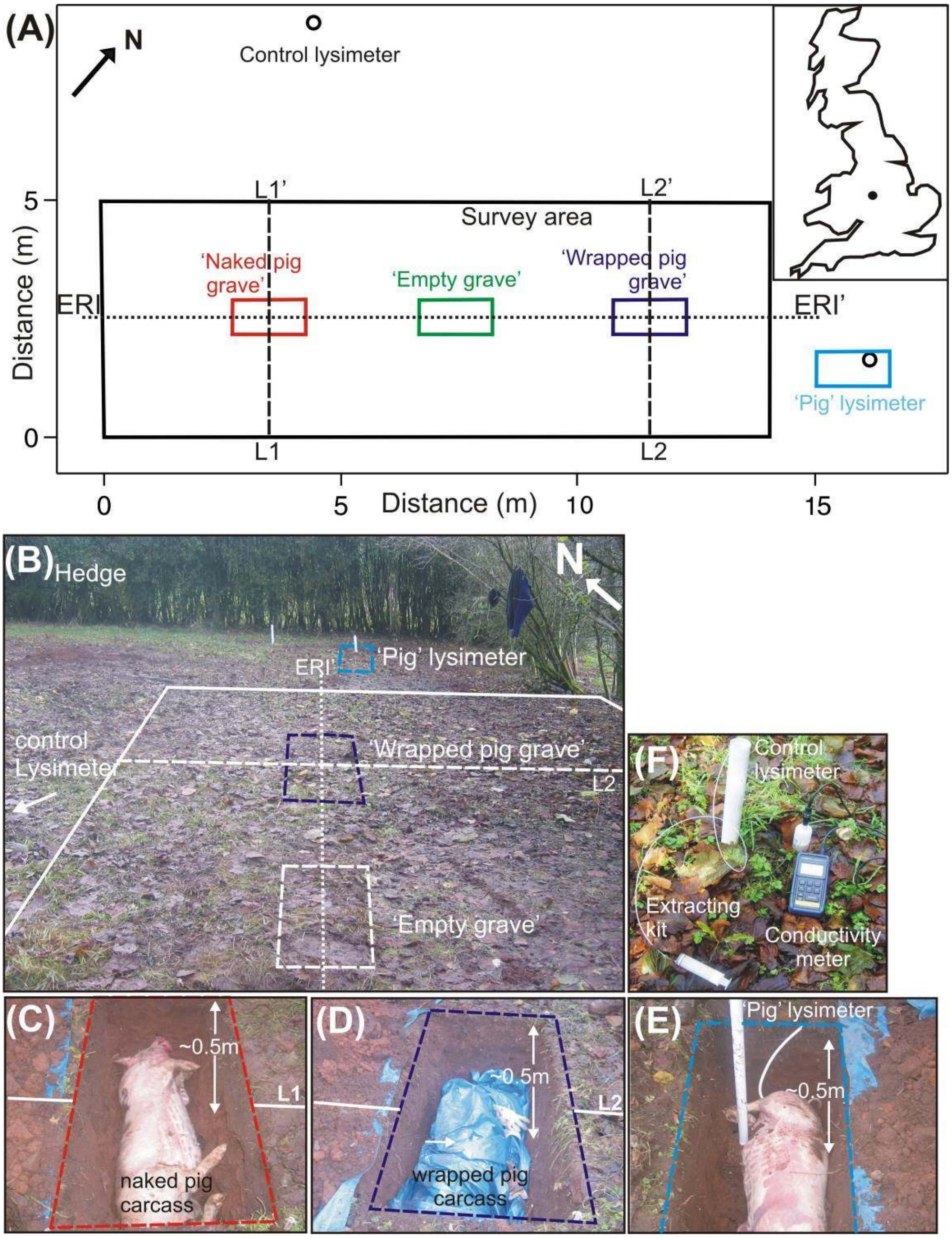

FIG. 2. (A) Map of survey area (dashed rectangle) with graves, ERI profile line, lysimeter positions and UK location map (inset). (B) Study site, (C) 'naked pig grave', (D) 'wrapped pig grave', (E) 'pig lysimeter grave' and (F) soil 'fluid' measurement photographs respectively. Modified from (25).

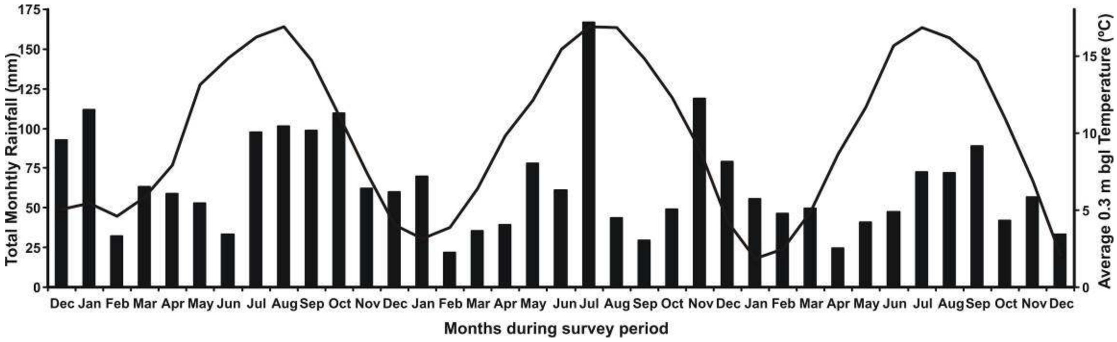

FIG. 3. Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the three-year study period.

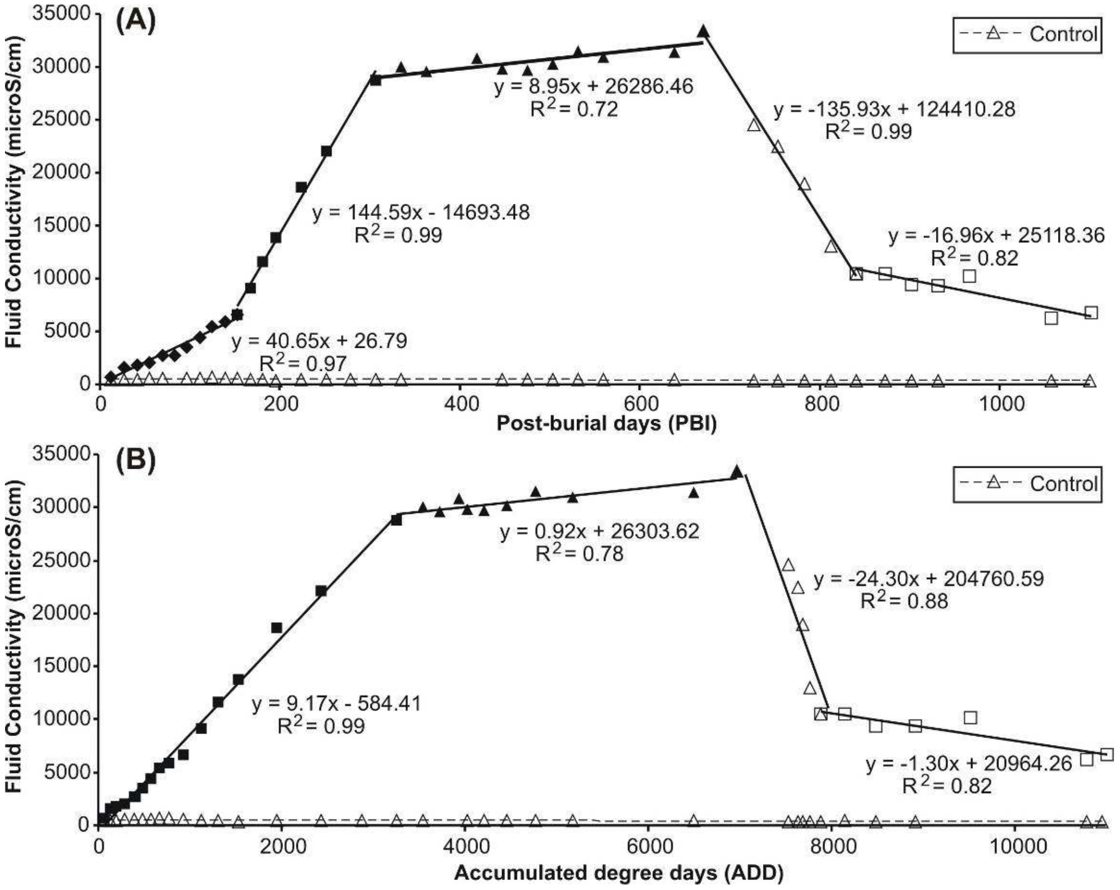

FIG. 4. (A) Measured pig leachate (solid line) and background (dashed line) soilwater fluid conductivity values over the three year survey period. (B) Measured soil water conductivity versus accumulated degree day (ADD) plot produced from (A) by summing average daily 0.3m bgl after burial temperatures (see text). Best-fit

linear correlation formulae and confidence (R^2) values are also shown. Modified from (26).

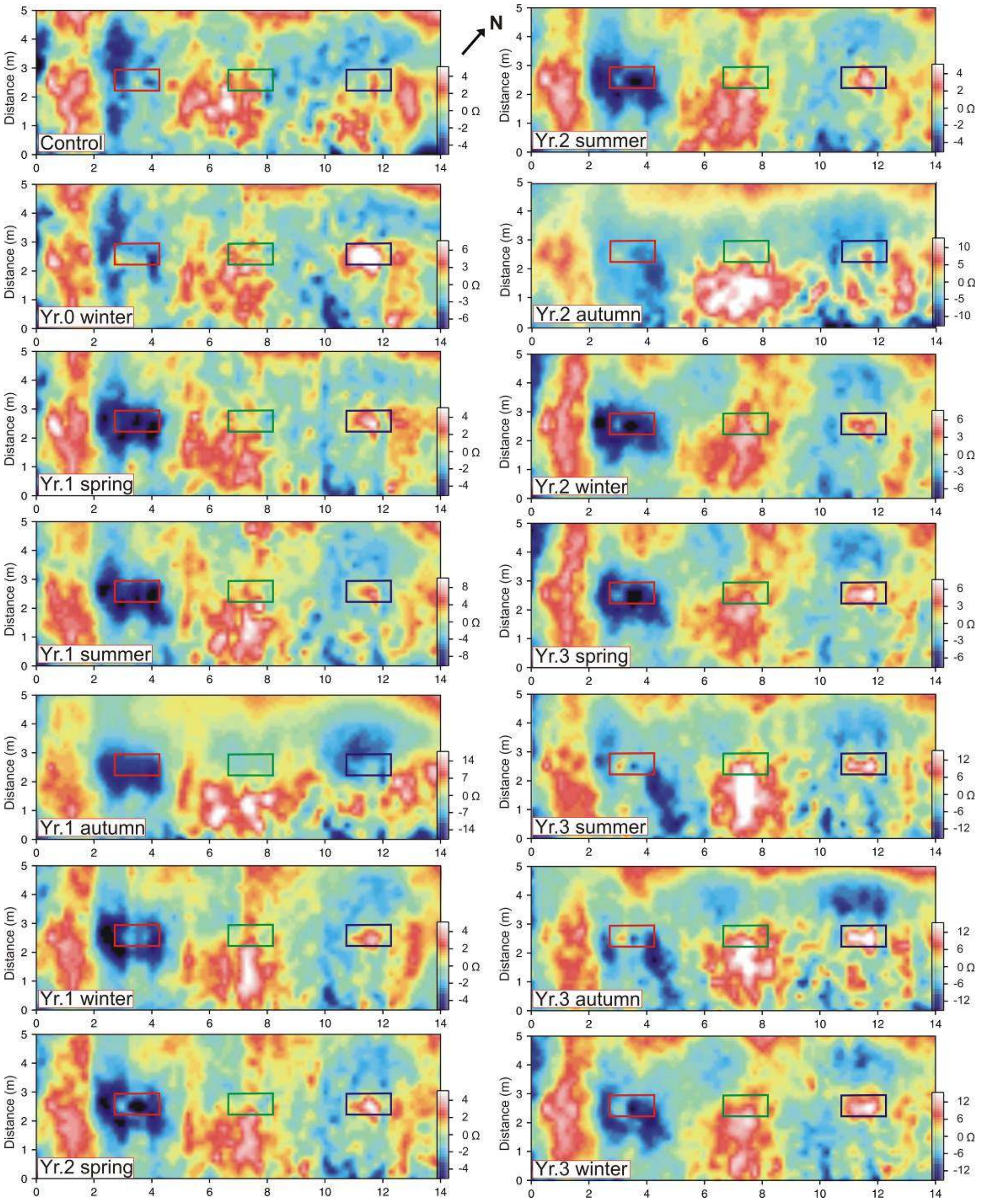

FIG. 5. Selected (year and seasons shown) fixed-offset processed resistivity datasets. Red, green and blue rectangles indicate positions of 'naked pig', 'empty' and 'wrapped pig' graves respectively (see Fig. 2A). Modified from (25).

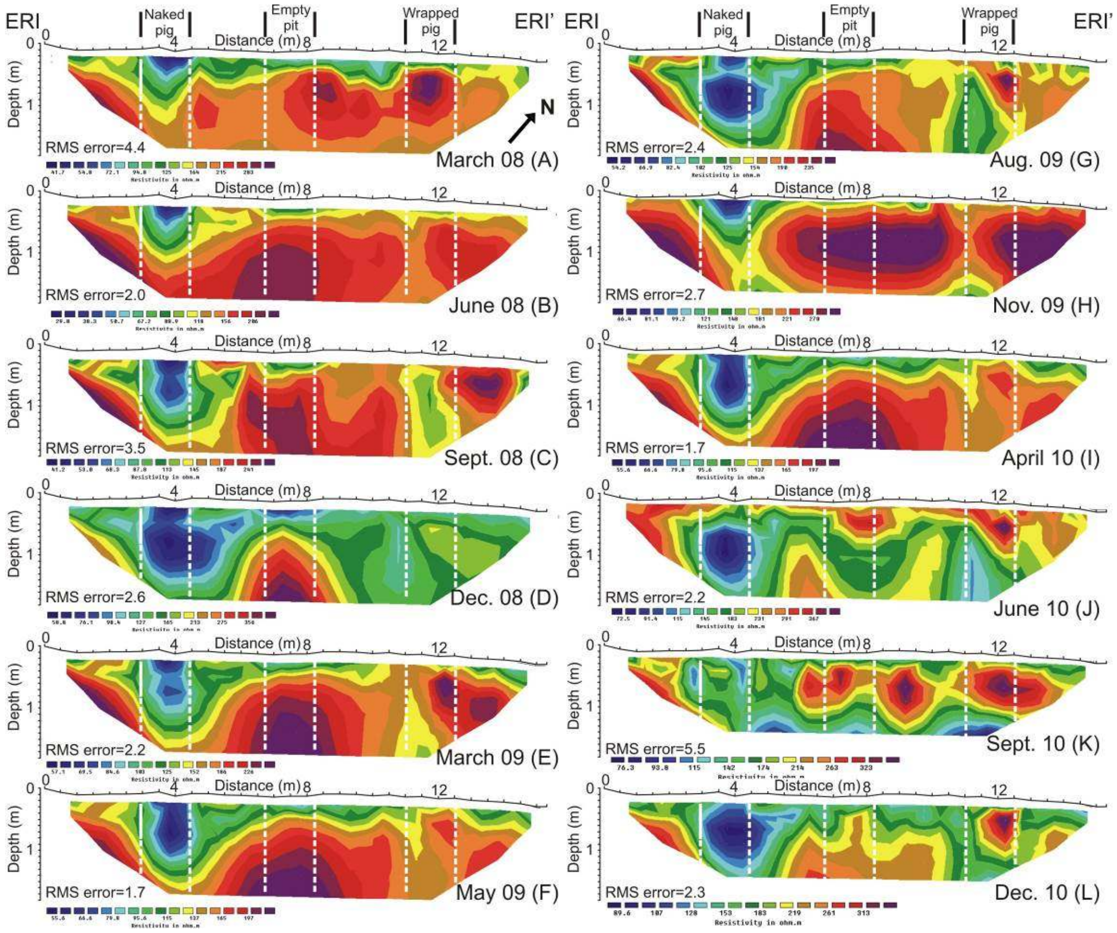

FIG. 6. Individually inverted 2D Electrical Resistivity Imaging (ERI) profiles collected during this study; model inversion errors (RMS) are indicated. Positions of ‘naked pig’, ‘empty’ and ‘wrapped pig’ graves are also shown (dashed lines). See Fig. 2A (ERI/ERI’) for location.

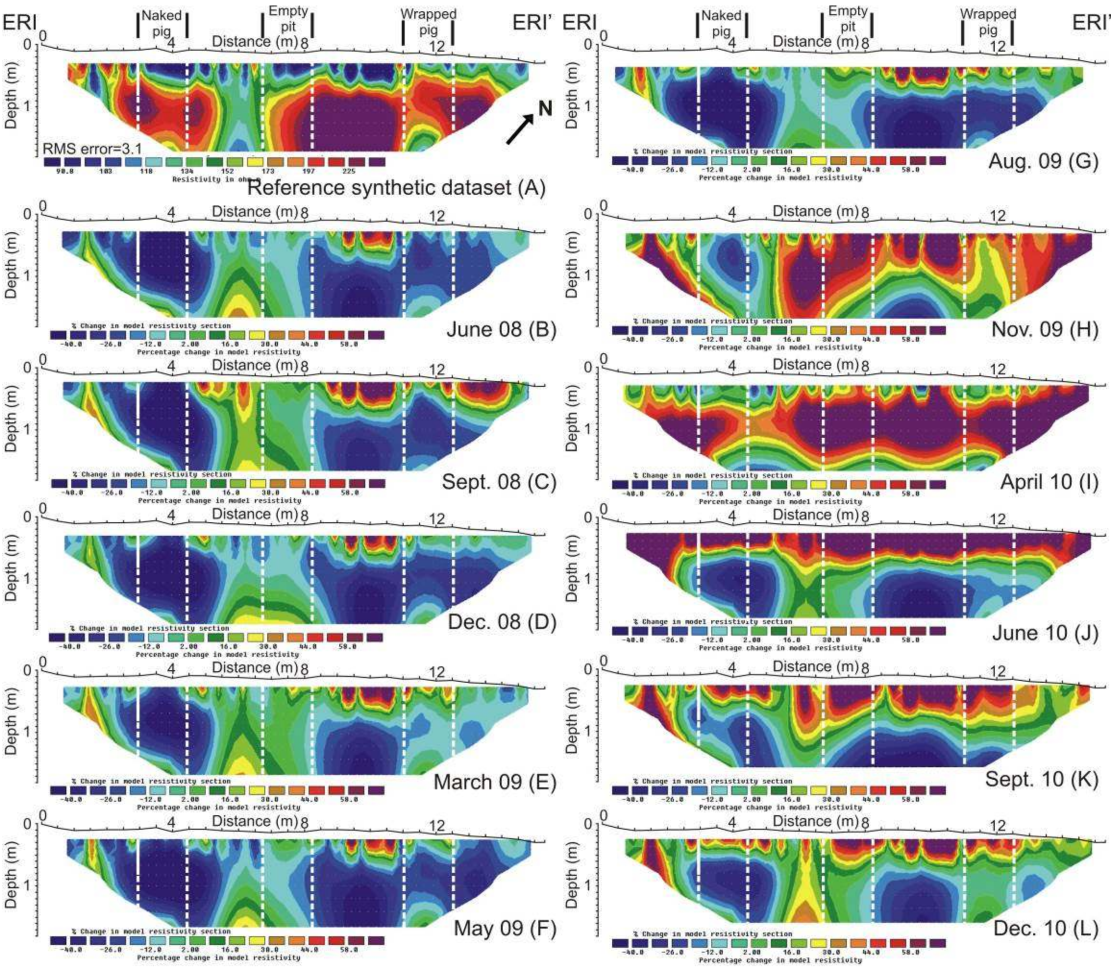

FIG. 7. Time-lapse ERI profiles where percentage changes in resistivity are shown relative to the March 2008 reference data set. Resistivity change contour scales are the same for all profiles; areas of dark blue represent relatively decreasing resistivity and areas of light blue through to purple represents relatively increasing resistivity compared to the reference dataset. See Fig. 2A (ERI/ERI') for location.

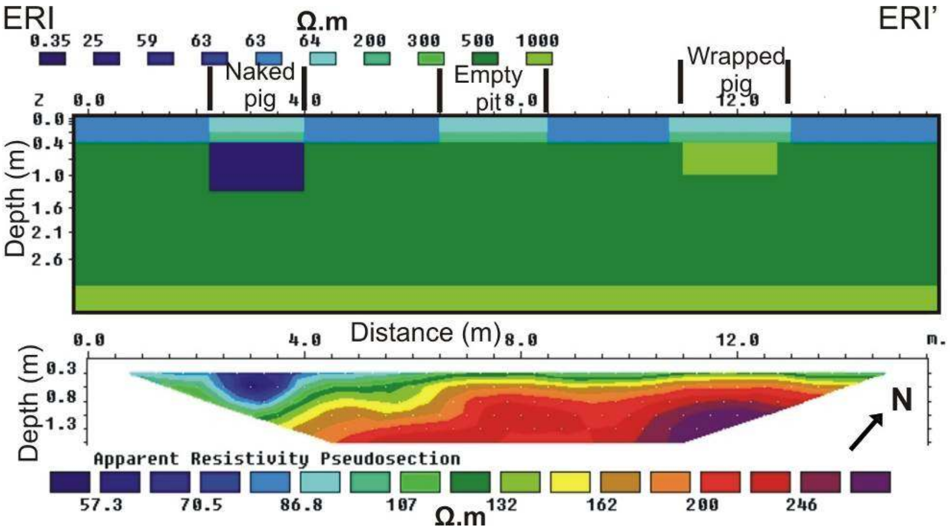

FIG. 8. Test site resistivity 2D model 2 years after burial, with their respective synthetic ERI Wenner profile shown below. Resistivity values are field calibrated from either contemporaneous resistivity and ERI surveys or from fluid conductivity measurements (see text). See Fig. 2A (ERI/ERI’) for location.

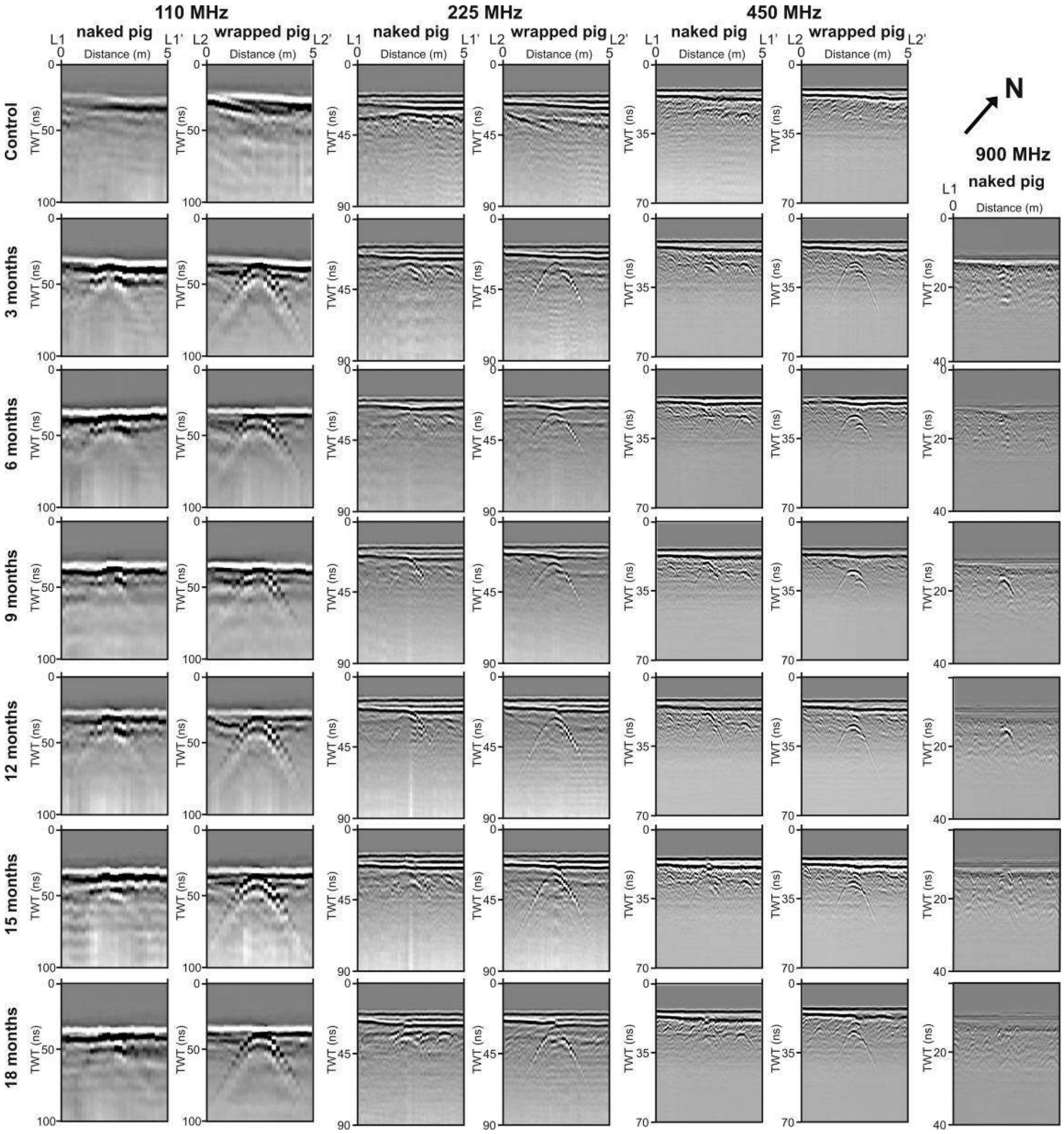

FIG. 9(A). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles that bisect the naked and wrapped pig ‘graves’ respectively (Fig. 2A for location) that include control profiles and data collected from 0 to 18 months after burial.

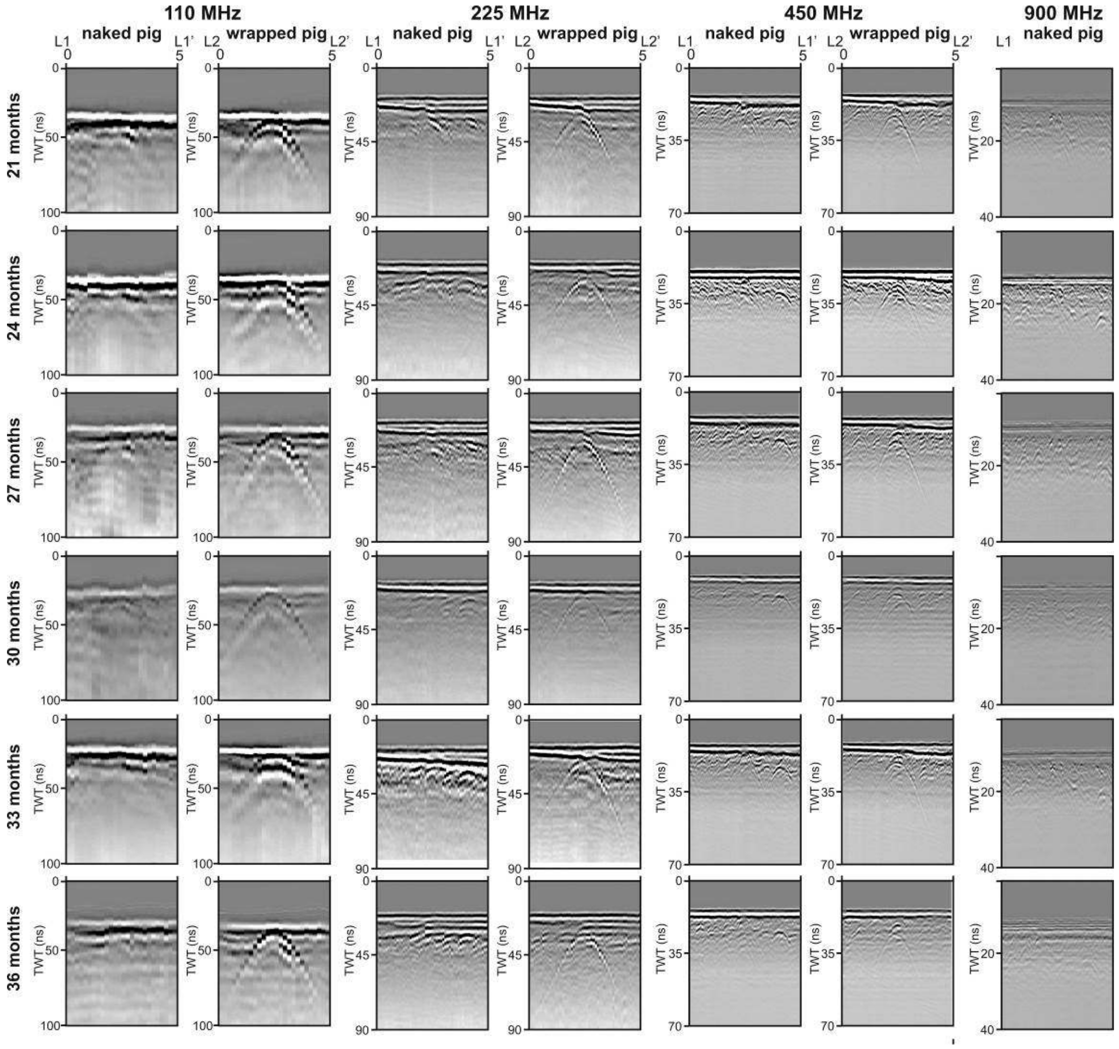

FIG. 9(B). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles that bisect the naked and wrapped pig 'graves' respectively (Fig. 2A for location) that include data collected from 21 to 36 months after burial.

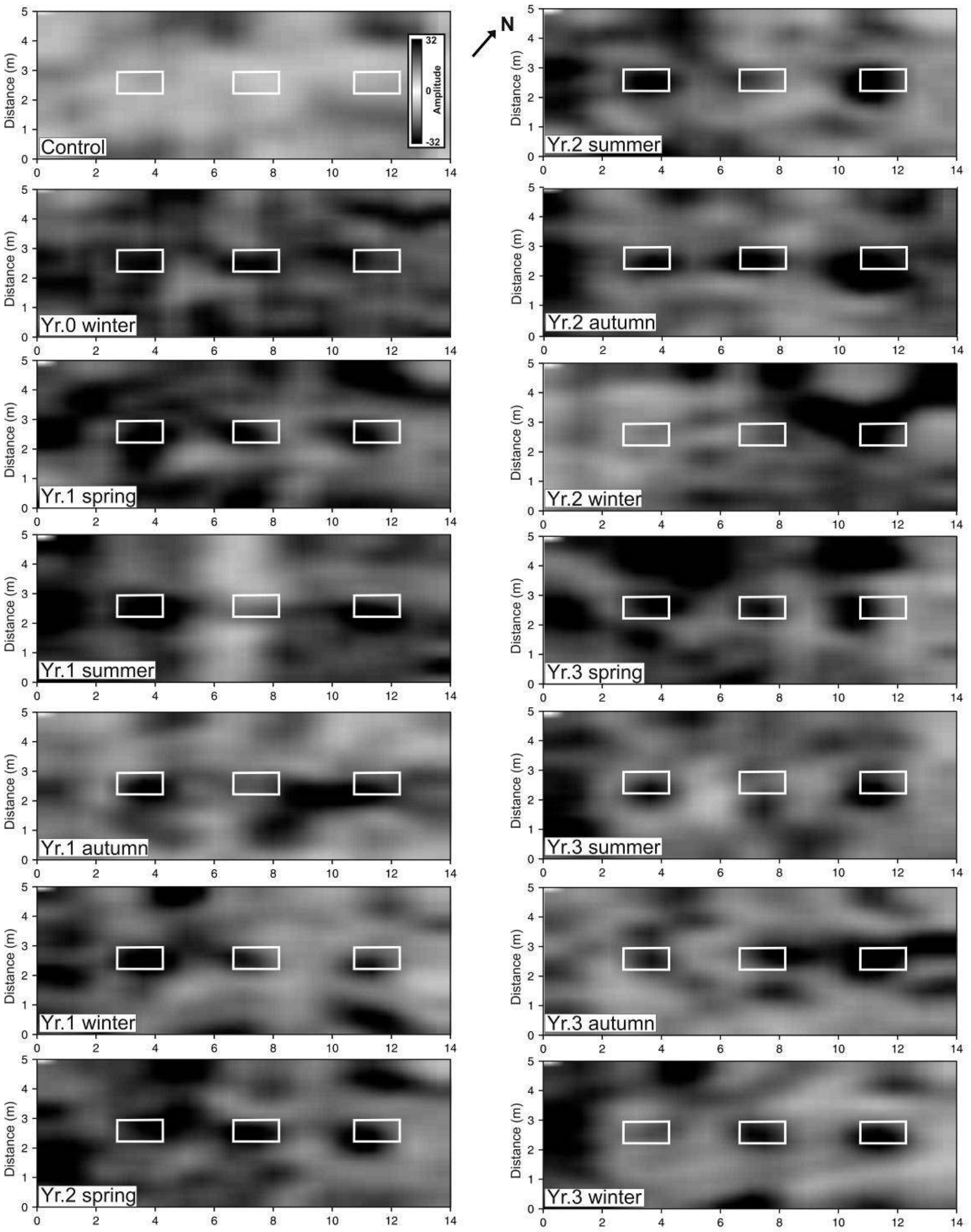

FIG. 10(A). 110 MHz frequency, quarterly GPR processed ‘time-slice’ datasets. Common amplitude scale shown in control dataset. Dotted squares indicate ‘graves’ (Fig. 2A for location).

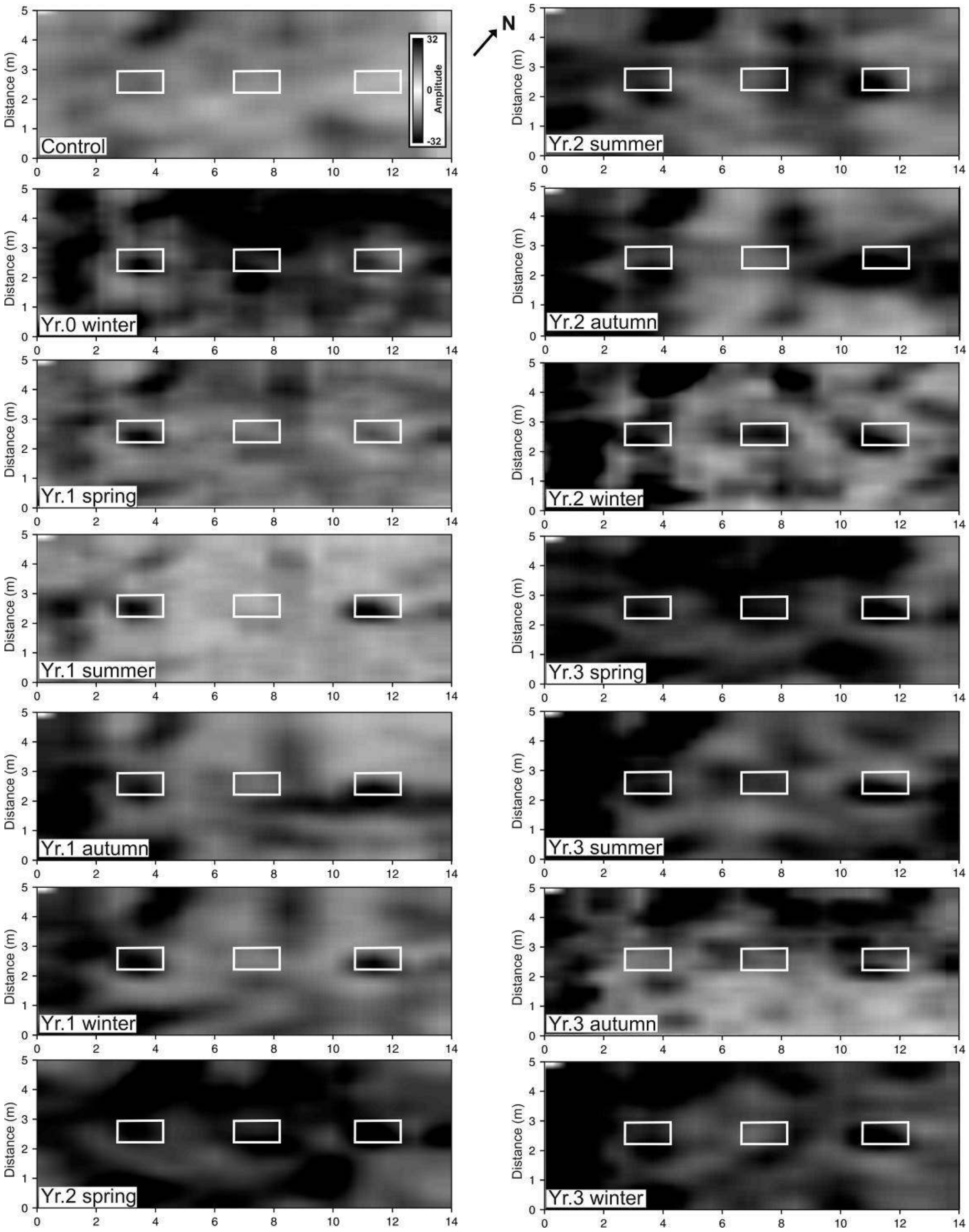

FIG. 10(B). 225 MHz frequency, quarterly GPR processed ‘time-slice’ datasets. Common amplitude scale shown in control dataset. Dotted squares indicate ‘graves’ (Fig. 2A for location).

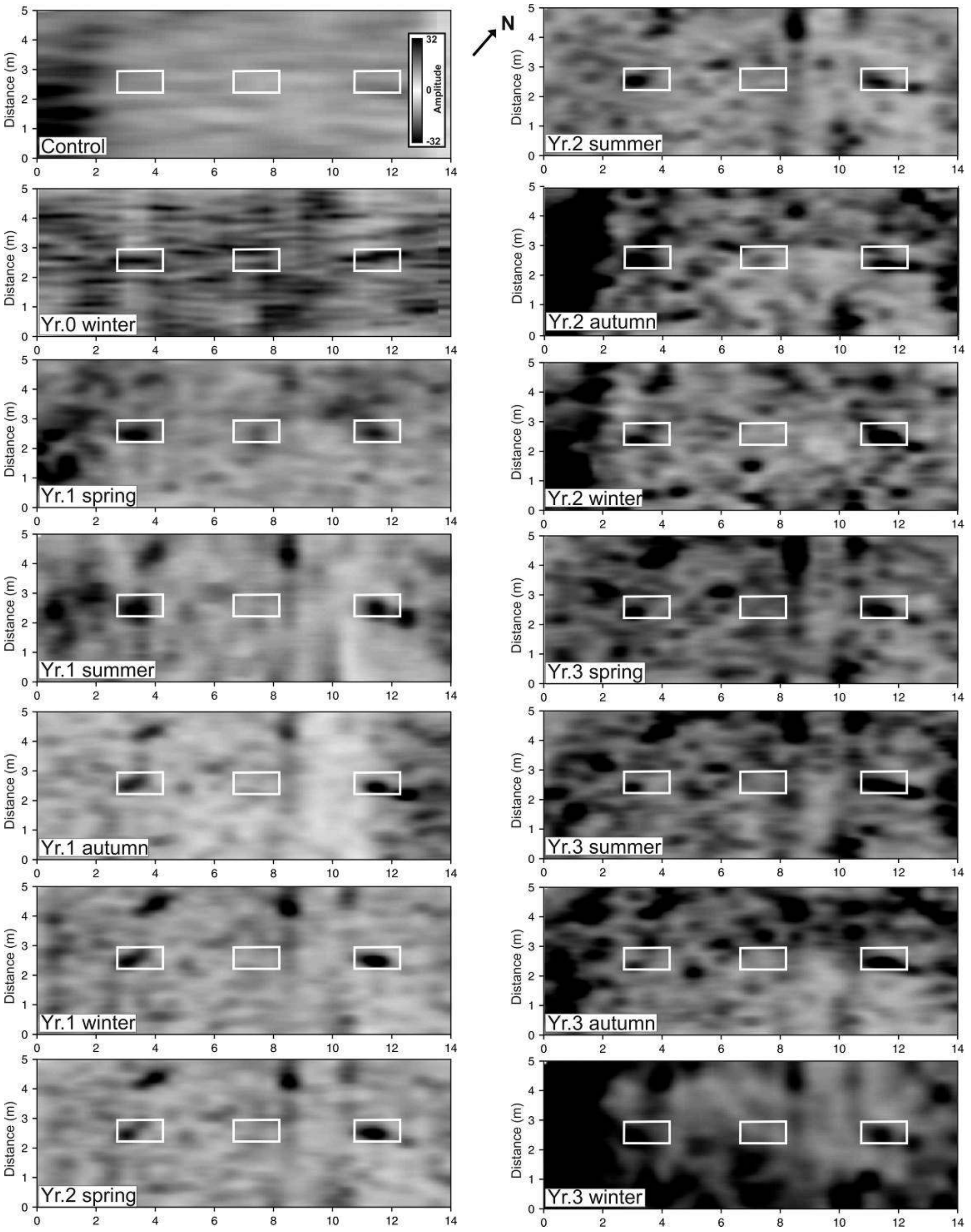

FIG. 10(C). 450 MHz frequency, quarterly GPR processed ‘time-slice’ datasets. Common amplitude scale shown in control dataset. Dotted squares indicate ‘graves’ (Fig. 2A for location).

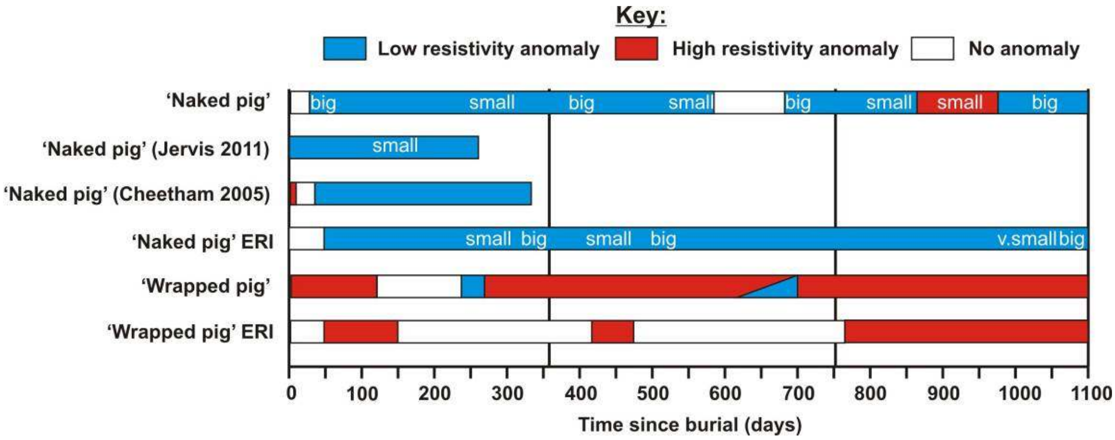

FIG. 11. Graphical timeline (vertical lines indicate time in years) showing resistivity changes over simulated graves. Relative anomaly sizes are also noted. Two other named studies are shown for comparison. All graves were buried at 0.5 m bgl.

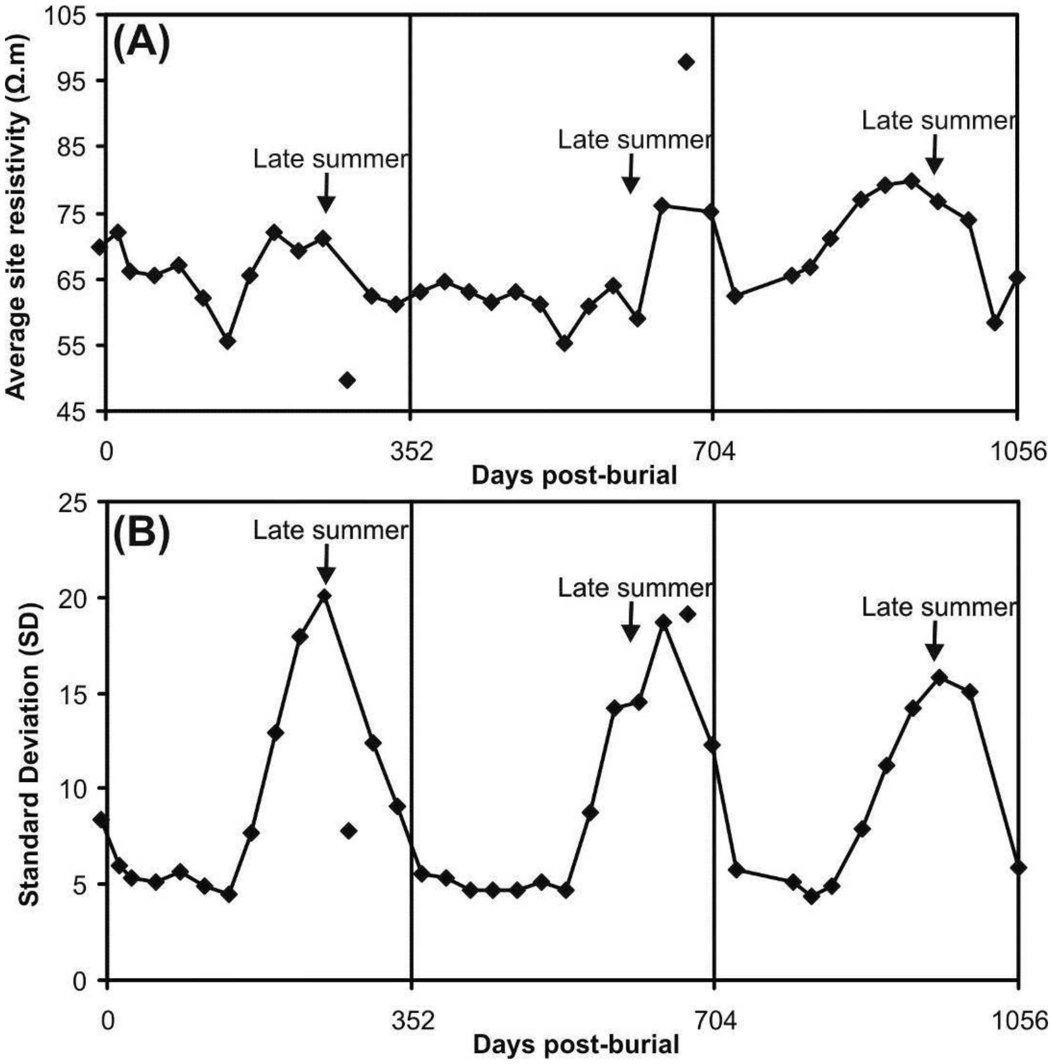

FIG. 12. Summary analysis plots of monthly fixed-offset resistivity data collected during this study. (A) Average resistivity values and (B) standard deviations (SD) for each survey. Note SD values are highest in late summer. Two survey outliers (collected at 280 and 672 days after burial) are shown but not included on respective lines.

TABLE:

Survey date(s)	**Survey day after burial[+]**	**Accumulated Degree Day (ADD)***	**Survey date(s)**	**Survey day after burial[+]**	**Accumulated Degree Day (ADD)***
Electrical resistivity (fixed-offset)^			28.05.2010	903	8,504
26.11.2007[#]	-10	-64	28.06.2010	934	8,976
21.12.2007	14	68	29.07.2010	965	9,501
04.01.2008	28	134	02.09.2010	1,000	10,065
01.02.2008	56	287	01.10.2010	1,029	10,486
29.02.2008	84	416	28.10.2010	1,056	10,782
28.03.2008	112	578	03.12.2010	1,092	11,026
25.04.2008	140	784	**ERI Profiles**		
23.05.2008	168	1,136	07.03.2008	91	454
20.06.2008	196	1,539	05.06.2008	181	1,314
18.07.2008	224	1,965	01.09.2008	269	2,727
15.08.2008	252	2,446	04.12.2008	363	3,732
12.09.2008	280	2,892	06.03.2009	455	4,080
10.10.2008	308	3,269	20.05.2009	530	4,765
07.11.2008	336	3,548	11.08.2009	613	6,083
05.12.2008	364	3,736	13.11.2009	707	7,371
02.01.2009	392	3,847	20.04.2010	865	8,084
30.01.2009	420	3,936	28.06.2010	934	8,976
27.02.2009	448	4,041	28.09.2010	1,026	10,446
27.03.2009	476	4,218	03.12.2010	1,092	11,026
24.04.2009	504	4,475	**GPR surveys**		
22.05.2009	532	4,789	04-05.12.2007[#]	-3 - -2	-14 - -7
19.06.2009	560	5,199	04-06.03.2008	88 - 90	439 - 448
17.07.2009	588	5,677	26-27.05.2008	171 - 172	1,176 – 1,187
14.08.2009	616	6,137	26-27.08.2008	263 - 264	2,625 – 2,642
11.09.2009	644	6,589	10-13.11.2008	339 - 342	3,573 – 3,595
09.10.2009	672	6,985	02-05.03.2009	451 - 454	4,059 – 4,076
06.11.2009	700	7,310	22-23.06.2009	563 - 564	5,243 – 5,258
04.12.2009	728	7,536	13-14.08.2009	615 - 616	6,119 – 6,137
30.12.2009	754	7,642	09-10.11.2009	703 - 704	7,337 – 7,345
08.02.2010	794	7,722	03-04.03.2010	817 - 818	7,781 – 7,784
02.03.2010	816	7,778	22-23.06.2010	928- 929	8,870 – 8,888
25.03.2010	839	7,880	28-29.09.2010	1,026 –27	10,446 – 460
30.04.2010	875	8,181	06-07.12.2010	1,092-93	11,033 - 035

TABLE 1. Summary of geophysical data collected during this study. [+]Burial date was 7th December 2007. *ADD date based on average daily site temperatures at 0.3 m bgl (see text). ^Note ground water conductivity measurements were collected the day before monthly surveys. [#]First surveys for fixed-offset resistivity and GPR datasets were controls.