

**PAPER****GENERAL**

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## Geophysical Monitoring of Simulated Clandestine Graves Using Electrical and Ground-Penetrating Radar Methods: 0–3 Years After Burial<sup>\*,†</sup>

**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. Multigeophysical surveys were collected over a 3-year monitoring period. Bulk ground resistivity, electrical resistivity imaging, multifrequency ground-penetrating radar (GPR), and 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- to 900-MHz frequency surveys showed the wrapped burial could be detected throughout, with the “naked” burial mostly resolved. Two hundred and twenty-five megahertz frequency GPR data were optimal. “Soil-water” analyses showed rapidly increasing (year 1), slowly increasing (year 2), and decreasing (year 3) 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). While 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 utilized, albeit sporadically, in criminal search investigations (Harrison, personal communication).

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 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 characterized (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 3 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 0.5-m bgl depth has been used, based on a 0.6-m depth bgl average from 87 discovered U.S. burials (27) 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 (10,27) were usually rectangular in planview, mostly hurriedly hand dug using garden implements, and usually just large

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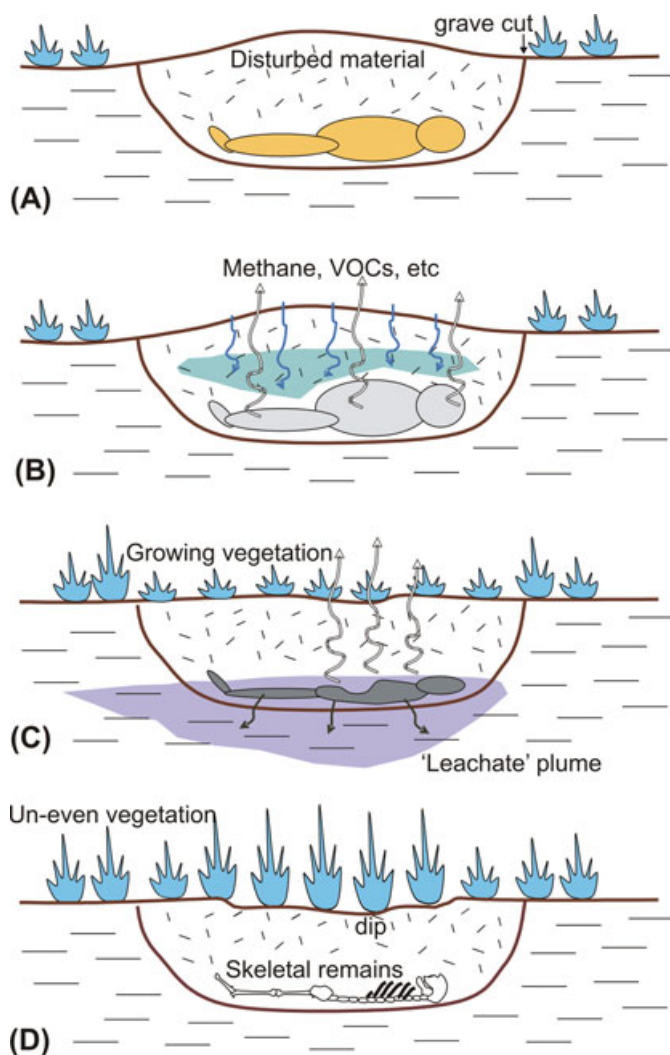


FIG. 1—Four likely sequential stages of clandestine burial. (A) Recent burial, surface expression is most obvious. (B) Early decomposition with cadaver dogs and/or methane probes being most useful. (C) Late-stage decomposition with conductive “leachate” plume that should be resolved by electrical methods.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

enough to deposit the victim before being backfilled with excavated soil and associated surface debris. Manhein (27) 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 a *naked* and *wrapped* burial, although it is emphasized 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 utilized to search for clandestine graves (20,25,28). Electrical resistivity methods were selected because 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 (15,26,28–30). 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 data sets 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 that do show

anomalies (31), magnetic results over simulated recent clandestine burials in a variety of depositional environments have proved to be unpromising for search teams (32).

The aims of this 3-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 to allow comparisons with other research studies and criminal search investigations. Basic forensic search questions that will be addressed by this study were as follows: First, could electrical resistivity fixed-offset surveys successfully locate both simulated clandestine burials? And if so, how long were they geophysically detectable for? Second, could GPR surveys successfully locate both simulated clandestine burials throughout the 3-year monitoring period? And if so, how long were they geophysically detectable for? And finally, which dominant frequency antenna was optimal to detect them? Third, when was the optimal time (both up to 3 years postburial and seasonally) to undertake a forensic GPR or electrical resistivity geophysical search survey? Fourth, what advantages do 2D electrical resistivity imaging (ERI) forensic surveys have over other electrical probe configurations or indeed other techniques? Fifth, what effect does soil type have on a forensic geophysical survey being successful? Sixth, what was important to do when processing electrical resistivity data sets? Seventh, what was important to do when processing GPR survey data sets? 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, U.K. The local climate is temperate, which is typical for the United Kingdom (33). The study site was a grassed, small rectangular area (~25 m × ~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 (34). Local soil maps, however, designated this area as made ground, owing 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 (35). Therefore, for a 2-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 2 days would be 27 ADDs. The local weather station data showed that

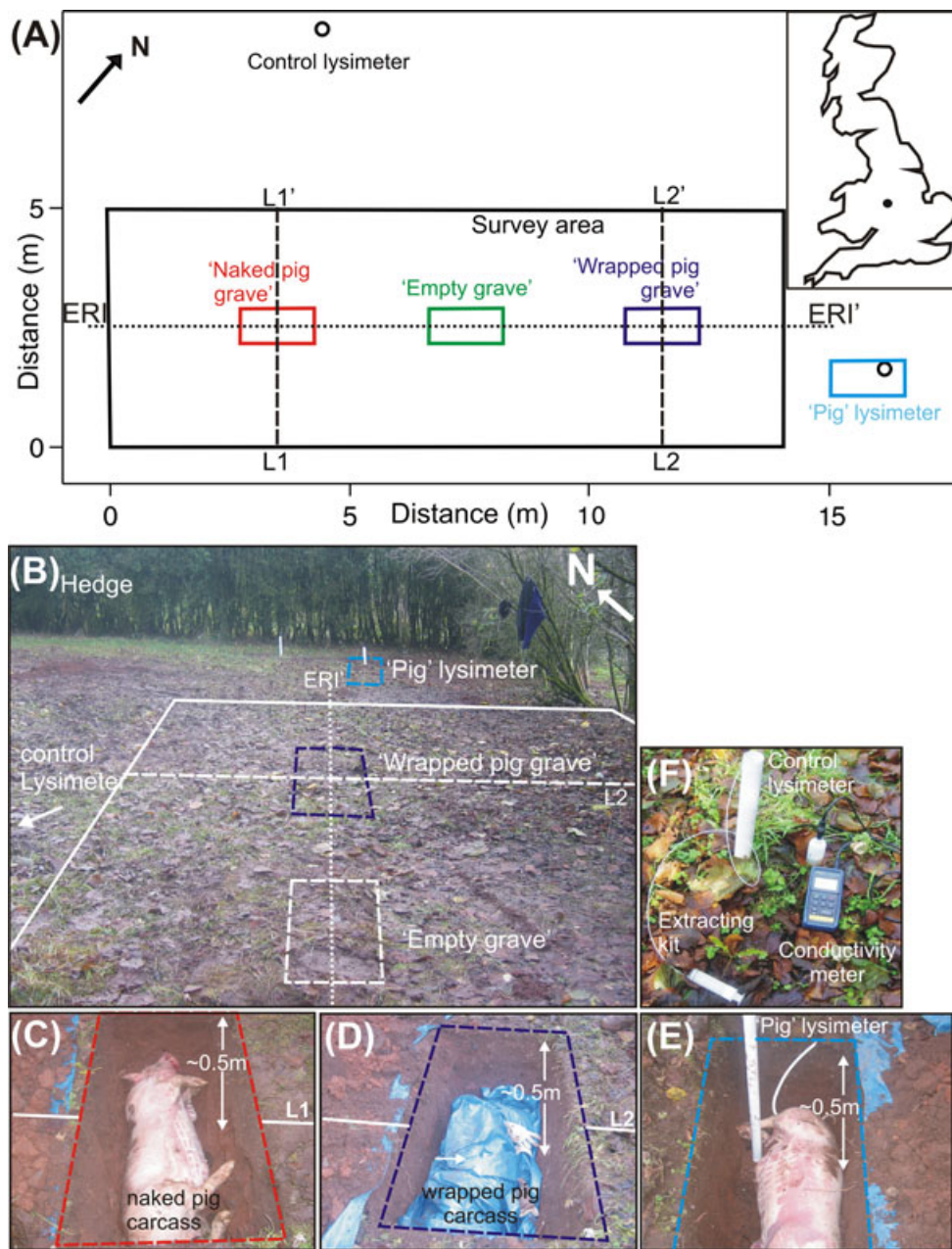


FIG. 2—(A) Map of survey area (dashed rectangle) with graves, electrical resistivity imaging profile line, lysimeter positions, and U.K. location map (inset). (B) Study site, (C) “naked pig grave,” (D) “wrapped pig grave,” (E) “pig lysimeter grave,” and (F) soil “fluid” measurement photographs, respectively. Modified from (25).

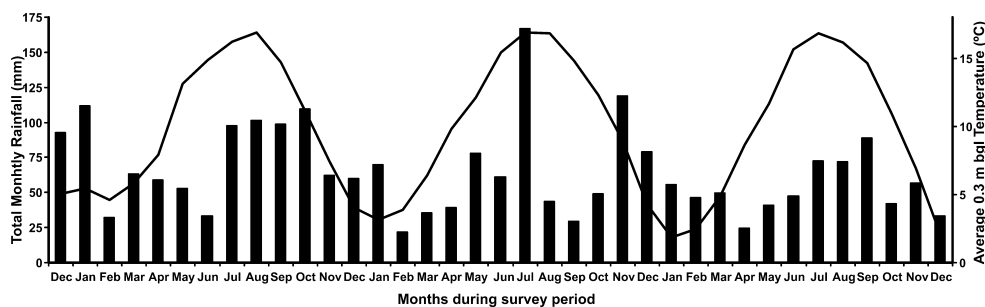


FIG. 3—Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the 3-year study period.

total monthly rainfall during the study period ranged from 21.6 to 166.7 mm, with an overall monthly average of 64.7 mm. Average monthly air temperatures ranged from  $-1.2^{\circ}\text{C}$  to  $15.8^{\circ}\text{C}$ , with an overall monthly average of  $8.7^{\circ}\text{C}$ . Note at 0.3 m bgl, the average temperature was  $9.8^{\circ}\text{C}$  for the 3-year monitoring period.

### *Simulated Graves*

The Human Tissue Act (2004) prevents human cadavers from being used for research in the United Kingdom 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 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 (30,36). Five simulated graves were created at the site (Fig. 2A). Three of the graves were used for the repeat geophysical surveys, while groundwater 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 December 7th, 2007. For each grave, the turf was removed and *c.* 1.5-m-long, 0.75-m-wide, and 0.6-m-deep bgl pits were excavated. The three pig cadavers, which weighed  $\sim 80$  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  $\times$  2.7 m (product number: D00065; Duratool Corporation, Taichung, Taiwan). The pigs had been deceased for  $< 5$  h 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 Groundwater Conductivity Data Collection*

Within the "pig" lysimeter grave outside of the survey area (Fig. 2A), a groundwater sample lysimeter was placed between the carcass and the grave wall (Fig. 2E and [37]). The porous end cap of a model 1900 (SoilMoisture Equipment Corporation<sup>TM</sup>, Santa Barbara, CA) soil-water 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  $\sim 10$  m from the survey area by digging a narrow hole ( $\sim 0.3$  m  $\times$   $\sim 0.3$  m) to  $\sim 0.6$ -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 groundwater samples from both of the lysimeters 2 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 meter (mS/m) immediately after collection using a multiline P4 multiparameter meter (WTW GmbH, Weilheim, Germany) (Fig. 2F). The data collection took  $\sim 0.5$  h each time. See (37) for more information.

### *Bulk Ground (Fixed-Offset) Resistivity Data Collection and Processing*

A resistivity survey was conducted at the study site 11 days before burial for comparison with the postburial 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  $\times$  14 m and sloped by *c.*  $3^{\circ}$  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<sup>TM</sup> Research, Bradford, UK) 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, while 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 *c.* 0.15 m into the ground. For each measurement, the mobile probes were pushed *c.* 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 year 1 onward, a RM15 (Geoscan<sup>TM</sup> 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  $\sim 2$  h to acquire.

Resistivity survey data were processed using the Generic Mapping Tools software (40). To aid visual interpretation of the data, a minimum curvature gridding algorithm (41) was used to interpolate each data set to a cell size of 0.125 m  $\times$  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 data sets collected at different times of the year. Therefore, survey data were normalized by dividing each data set by its standard deviation. All processed, normalized data sets then had a zero mean value and standard deviation units, which made comparisons between different resistivity survey data sets possible.

### *Electrical Resistivity Imaging Data Collection and Processing*

A 2D ERI survey line orientated SW-NE (Fig. 2A,B) was permanently marked with plastic pegs and surveyed at *c.* 3-monthly intervals, starting at 3 months after burial (Table 1). The survey profile was 15.5 m long and bisected all three graves (Fig. 2A), with 32  $\times$  0.3 m long stainless steel electrodes placed  $\sim 0.1$  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

TABLE 1—Summary of geophysical data collected during this study.

Survey Date(s)	Survey Day After Burial*	Accumulated Degree Day <sup>†</sup>	Survey Date(s)	Survey Day After Burial*	Accumulated Degree Day <sup>†</sup>
Electrical resistivity (fixed-offset) <sup>‡</sup>			28.05.2010	903	8504
26.11.2007 <sup>§</sup>	-10	-64	28.06.2010	934	8976
21.12.2007	14	68	29.07.2010	965	9501
04.01.2008	28	134	02.09.2010	1000	10,065
01.02.2008	56	287	01.10.2010	1029	10,486
29.02.2008	84	416	28.10.2010	1056	10,782
28.03.2008	112	578	03.12.2010	1092	11,026
25.04.2008	140	784	Electrical Resistivity Imaging Profiles		
23.05.2008	168	1136	07.03.2008	91	454
20.06.2008	196	1539	05.06.2008	181	1314
18.07.2008	224	1965	01.09.2008	269	2727
15.08.2008	252	2446	04.12.2008	363	3732
12.09.2008	280	2892	06.03.2009	455	4080
10.10.2008	308	3269	20.05.2009	530	4765
07.11.2008	336	3548	11.08.2009	613	6083
05.12.2008	364	3736	13.11.2009	707	7371
02.01.2009	392	3847	20.04.2010	865	8084
30.01.2009	420	3936	28.06.2010	934	8976
27.02.2009	448	4041	28.09.2010	1026	10,446
27.03.2009	476	4218	03.12.2010	1092	11,026
24.04.2009	504	4475	Ground-Penetrating Radar Surveys		
22.05.2009	532	4789	04.12.2007 <sup>§</sup>	-3	-14
19.06.2009	560	5199	04.03.2008	88	439
17.07.2009	588	5677	26.05.2008	171	1176
14.08.2009	616	6137	26.08.2008	263	2625
11.09.2009	644	6589	10.11.2008	339	3573
09.10.2009	672	6985	02.03.2009	451	4059
06.11.2009	700	7310	22.06.2009	563	5243
04.12.2009	728	7536	13.08.2009	615	6119
30.12.2009	754	7642	09.11.2009	703	7337
08.02.2010	794	7722	03.03.2010	817	7781
02.03.2010	816	7778	22.06.2010	928	8870
25.03.2010	839	7880	28.09.2010	1026	10,446
30.04.2010	875	8181	06.12.2010	1092	11,033

\*Burial date was December 7th, 2007.

<sup>†</sup>Accumulated degree day date based on average daily site temperatures at 0.3 m bgl (see text).

<sup>‡</sup>Note groundwater conductivity measurements were collected the day before monthly surveys.

<sup>§</sup>First surveys for fixed-offset resistivity and ground-penetrating radar datasets were controls.

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 3 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 data sets were semi-automatically collected by a Campus™ TIGRE (Campus International Products Ltd., Dunstable, UK) system using ImagerPro™ 2006 data acquisition software (Media Cybernetics Inc., Bethesda, MD). Electrode contact resistances were checked before each profile was collected and repositioned if necessary to gain equivalent contacts across each survey line, following standard practices (44). Ten “n” levels were collected for each survey. Each electrode position was surveyed during the first survey using Leica™ 1200 differential global positioning system (dGPS) Real-Time Kinematic equipment (Leica Geosystems AG, Heerbrugg, Switzerland). The ERI surveys each took ~2 h to acquire.

Raw ERI data sets were then individually processed and inverted utilizing a least-squares inversion approach using Geotomo™ Res2Dinv v.3.55 software (Geotomo Software, Penang, Malaysia) in accordance with resistivity surveying recommendations (45). The bottom four “n” levels were removed, and half cell spacing was

utilized 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. Finalized models of true resistivity sections were lastly created.

Geotomo™ Res2Dinv software also allowed ERI analysis of temporal changes in resistivity 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 utilized. A half cell spacing was also used to refine the model and reduce the impact of near-surface effects (see [48]). To focus on the graves rather than seasonal resistivity variations of the whole profile, the resistivity data were constrained and compared to data from the first ERI survey of the graves, that is, 3 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) using the site monitoring data for model calibration. Three models were generated to represent the site at years 1, 2, and 3 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  $0.35 \Omega \cdot \text{m}$  for the naked pig grave,  $59 \Omega \cdot \text{m}$  for the empty grave, and  $63.1 \Omega \cdot \text{m}$  for the surrounding model top layer, respectively. Deeper layer 2 cell values of  $200 \Omega \cdot \text{m}$  and  $500 \Omega \cdot \text{m}$  for the “wrapped pig” grave were obtained from ERI surveys and “grave soil” conductivity measurements. The computer program 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 Data Collection and Processing*

Repeat GPR survey data sets were also collected within the survey area (Fig. 2A) at *c.* 3-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 (Sensors & Software Inc., Mississauga, Ontario, Canada) utilized 110-, 225-, 450-, and 900-MHz dominant frequency antennae to collect four data sets for each repeat survey postburial to investigate these commonly used frequencies and the less used ones. It was decided that 50- and 1200-MHz dominant frequency data sets 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  $14 \text{ m} \times 5 \text{ m}$  survey area was GPR surveyed on 0.5-m spaced, 5-m-long SE-NW orientated, parallel survey lines by 110-, 225-, and 450-MHz dominant frequency antennae. Using 0.5-m spaced survey lines for the 450-MHz frequency data sets was because of time constraints—ideally 0.25-m spaced survey lines should be utilized for this frequency. The transmitter antennae always led each profile for consistency purposes. The 900-MHz dominant frequency antennae were used to acquire data sets on 0.25-m spaced lines over a smaller area, centered over the “naked pig” grave (Fig. 3A). Radar trace spacings were 0.2, 0.1, 0.05, 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 data sets for consistency purposes. The GPR surveys took  $\sim 1 \text{ h}$ ,  $\sim 2.5 \text{ h}$ ,  $\sim 4 \text{ h}$ , and  $\sim 2 \text{ h}$  to acquire for the 110-, 225-, 450-, and 900- (subset) MHz dominant frequency data sets, 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 (Sandmeier Scientific Software, Karlsruhe, Germany). 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 to filter out nontarget “noise” and therefore make the target hyperbolae more pronounced. These steps were as follows: (i) subtracting the mean from traces (“dewowing”), (ii) picking first arrivals, (iii) applying static correction and moving the start times for traces in all profiles to 0 ns, (iv) applying a 1D Butterworth bandpass filter to remove low-amplitude frequencies, (v) background removal to reduce any “ringing” effect, and finally (vi) applying a Stolt migration in accordance with the target hyperbolae velocities. Last, horizontal time-slices of the four dominant frequencies data sets 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  $\sim 6 \text{ ns}$  (9–15 ns) time window containing the target hyperbolae to display absolute amplitude values.

## Results

### *Bulk Groundwater Conductivity*

Background soil-water conductivity measurements demonstrated that background values were consistent over the 3-year survey period (averaging  $444 \pm 0.1 \mu\text{S}/\text{cm}$  with 84 SD), whereas the pig leachate conductivity varied throughout the survey period (Fig. 4A). Pig leachate conductivity varied from  $729 \pm 0.1 \mu\text{S}/\text{cm}$  (12 days after burial) up to a maximum of  $33,400 \pm 100 \mu\text{S}/\text{cm}$  (671 days after burial) over the survey period. Conductivity changes during the first 2 years of burial are reported in (8). The “grave” conductivity values were twice the background values after only 2 weeks of burial. Leachate values could be grouped into five linear regressions: 0–150, 150–307, 307–671, 671–840, and 840–1057 after burial days, respectively (cf., Fig. 4A). The final conductivity measurements at the end of the survey period could not be obtained owing to prolonged cold conditions had frozen soil water and thus prevented extractions (December 2010 had an average site monthly air temperature of  $-1.2^\circ\text{C}$ ). 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 Fig. 4A). The second linear regression line represented the highest period of conductivity increase, increasing by  $\sim 144 \mu\text{S}/\text{cm}$  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 ( $\sim 2$  years), conductivity values rapidly decreased,  $\sim 136 \mu\text{S}/\text{cm}$  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 ADD following standard methods (35). This study had the advantage of having temperature probe measurement data available from the actual mid-cadaver depth ( $\sim 0.3 \text{ m}$  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  $67.1 \Omega$  (with  $49.6 \Omega$  minimum and  $97.8 \Omega$  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 Fig. 5 (see Fig. 2A for “grave” locations). These shown data sets are acquired at 3-monthly intervals, except the control data set (acquired before grave emplacement) and a survey collected 2 weeks after burial (see Table 1 for full survey list). The control data set showed the site was comparatively heterogeneous geophysically before burial, with significant areas of high resistivity

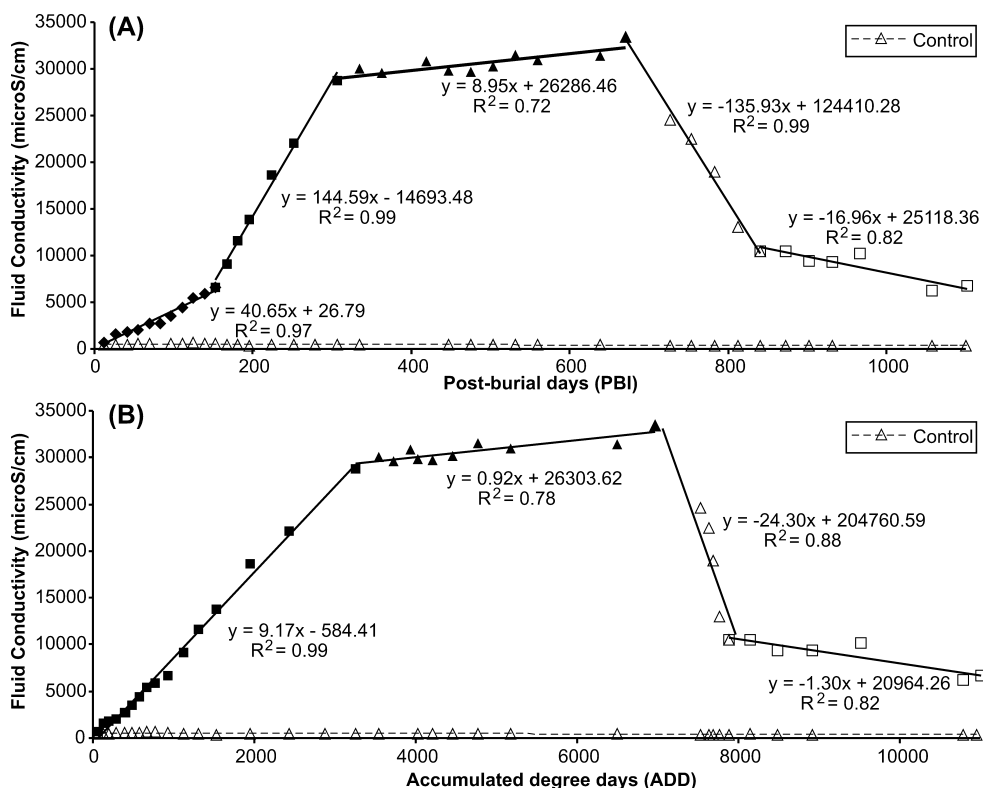


FIG. 4—(A) Measured pig leachate (solid line) and background (dashed line) soil-water fluid conductivity values over the 3-year survey period. (B) Measured soil-water conductivity versus accumulated degree day (ADD) plot produced from (A) by summing average daily 0.3 m bgl after burial temperatures (see text). Best-fit linear correlation formulae and confidence ( $R^2$ ) values are also shown. Modified from (26).

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 that acted as a control could not be geophysically detected throughout the survey period (middle rectangles in Fig. 5). The “naked pig” grave (left rectangles in Fig. 5) could predominantly be identified as a resistive low (left rectangular box) anomaly, when compared to background values, that appeared 4 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 planview area covered (cf., Fig. 5). The “wrapped pig” grave (right rectangles 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 surveys acquired over the study period were also consistent, with average ERI six “n” level survey resistivity values of  $161.8 \Omega \cdot \text{m}$  (with  $137.6 \Omega \cdot \text{m}$  minimum and  $206.0 \Omega \cdot \text{m}$  maximum, respectively), once de-spiking data processing had been undertaken. A summary of the 2D ERI profiles collected is graphically shown in Fig. 6 (see Fig. 2A for profile location and Table 1 for collection dates). An average inversion model error (root mean square) 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 neighboring 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  $\sim 1$  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,H).

The time-lapse difference ERI profiles shown in Fig. 7 show the percent change in resistivity compared to the reference (March 2008) data set. The time-lapse results reveal that up to 20 months postburial (see Fig. 7A–G) 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  $\sim 9$  months after burial shows the “empty” grave to have relative lower resistivity than the reference data set (Fig. 7C), an observation that is not obvious in the fixed-offset data of the same time period (280-day labeled 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 owing to summer (i.e., increased evapotranspiration, reduced rainfall) are typically observed during autumn (September–November) with significant (<150%) increases in resistivity (46). It is important

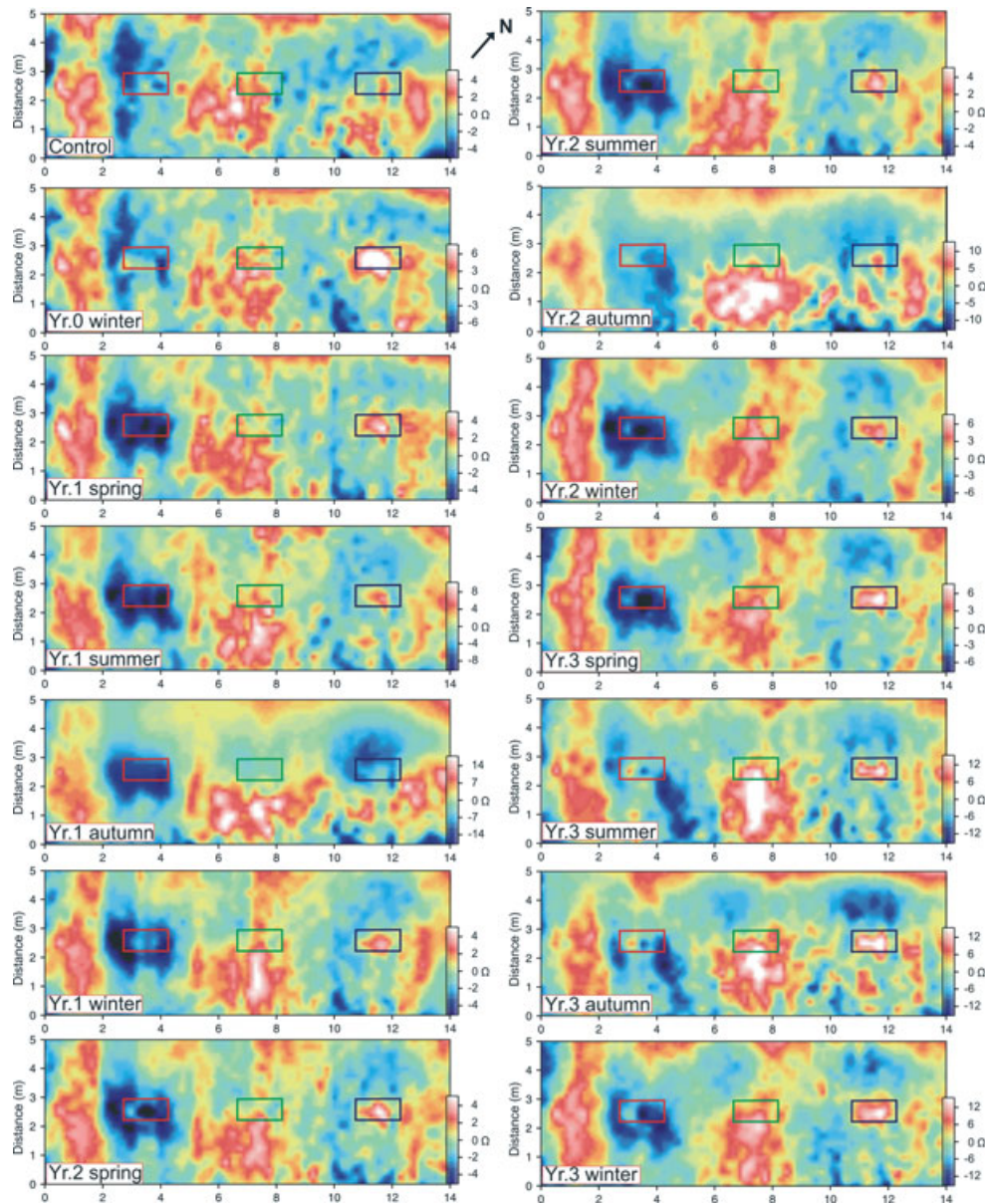


FIG. 5—Selected (year and seasons shown) fixed-offset processed resistivity datasets. Rectangles left to right indicate positions of “naked pig,” “empty,” and “wrapped pig” graves, respectively (see Fig. 2A). Modified from (25).

to note however that this is not clearly noticeable in the early post-burial stages (Fig. 7B–G) and is only prominent in the later post-burial stages (Fig. 7H–K). The other main observation from the time-lapse results is both the “naked pig” and “wrapped pig” graves have consistently increased resistivities from 2 years after burial onward, when compared to the reference data set (Fig. 7H–L). 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 1-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 2-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 not resolved in either profile. For the 3-year burial model, the synthetically generated ERI profile did not look that comparable to its equivalent survey ERI profile, similarly to the 1 year after burial data set. 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

Key 2D GPR profiles acquired through the survey period are shown in Fig. 9A,B (see Fig. 2A for profile locations). Preburial



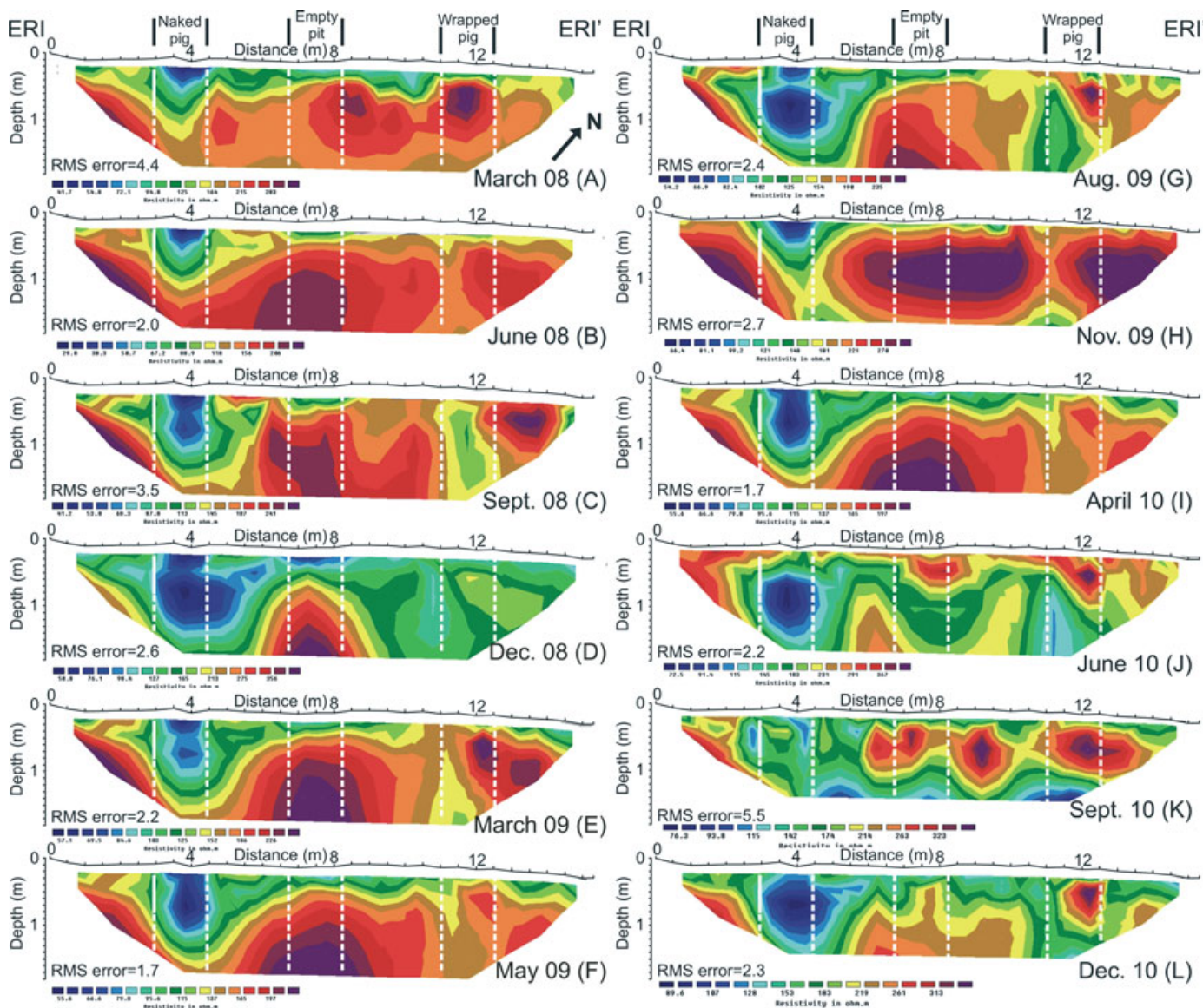


FIG. 6—Individually inverted 2D electrical resistivity imaging (ERI) profiles collected during this study; model inversion errors (root mean square) are indicated. Positions of “naked pig,” “empty,” and “wrapped pig” graves are also shown (dashed lines). See Fig. 2A (ERI/ERI’) for location.

profiles (to act as a control) are also shown, except for 900-MHz frequency data, which did not have a control data set 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,B). 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 2 years of burial (cf., Fig. 9A,B). 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 of 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,B). 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

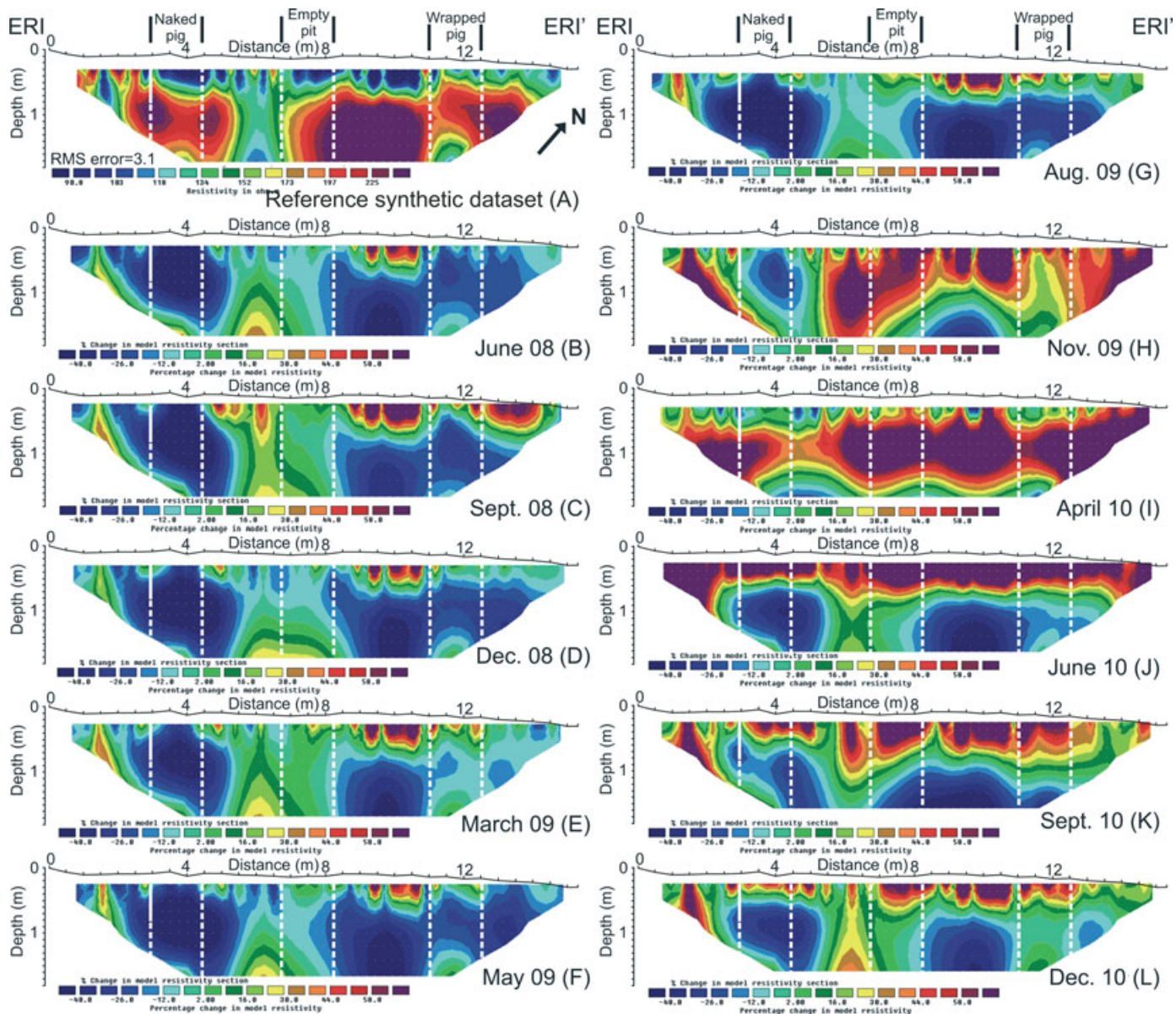


FIG. 7—Time-lapse electrical resistivity imaging (ERI) profiles where percent changes in resistivity are shown relative to the March 2008 reference dataset. Resistivity change contour scales are the same for all profiles; areas of dark represent relatively decreasing resistivity, and areas of light represent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

of 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,B). 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 data set 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 data sets. 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 3-year study period, except for the “naked pig” position in the year 2 and 3 winter data sets. 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 data sets. There were a number of radar anomalies also present within the data sets that were not associated with the target “grave” positions, notably in the year 0 winter, year 1 spring and summer, and year 2 and year 3 summer respective survey data sets (Fig. 10A).

The 225-MHz dominant frequency repeat survey time-slices generally showed variable results (Fig. 10B). The control data set did not show 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 data sets. 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

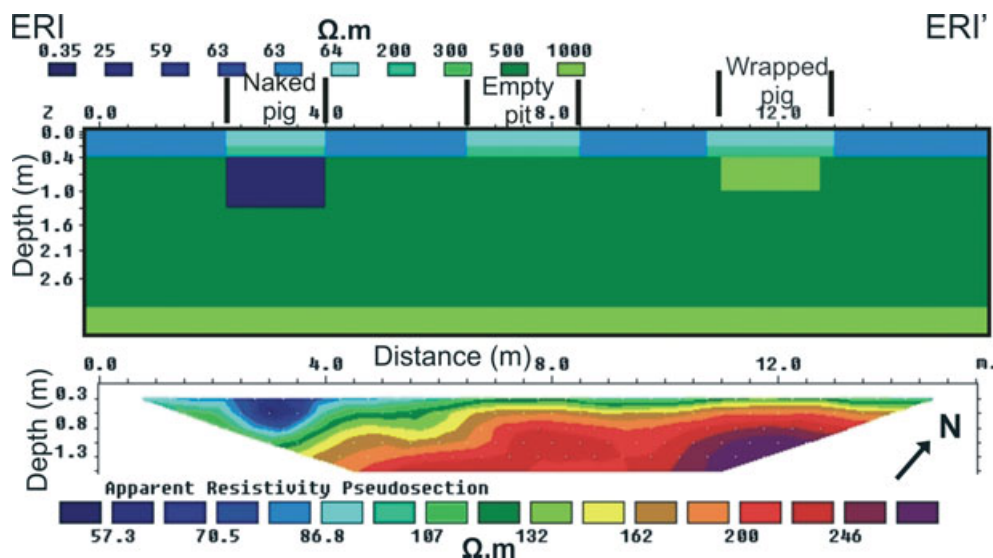


FIG. 8—Test site resistivity 2D model 2 years after burial, with their respective synthetic electrical resistivity imaging (ERI) Wenner profile shown below. Resistivity values are field calibrated either from contemporaneous resistivity and ERI surveys or from fluid conductivity measurements (see text).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

throughout the 3-year study period, except for the “naked pig” position in the year 2 and 3 autumn data sets. “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 data set. There were a number of radar anomalies also present within the data sets that were not associated with the target “grave” positions, especially from year 2 spring survey data sets onward (Fig. 10B), which would make locating the “target graves” in these data sets problematic.

The 450-MHz dominant frequency repeat survey time-slices generally showed variable results (Fig. 10C). The control data set did not show 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 data sets. 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 3-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 data sets that were not associated with the target “grave” positions, present in the year 0 winter survey and especially from year 2 autumn survey data sets onward (Fig. 10C), which would make locating the “target graves” in these data sets problematic.

## Discussion

This is the first published research to sequentially collect 3 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.

*First, 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 is 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 3 years after burial, owing 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 [37]). 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 (51) and inhibit microorganism activity (36), which therefore suggests a clandestinely buried body may be identifiable for longer if wrapped as compared to naked. Using all the resistivity data sets collected in this study, a graphical timeline diagram has been generated to show temporal anomaly variations throughout the survey period (Fig. 11). Both the (16) and (30) 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 planview size and relative

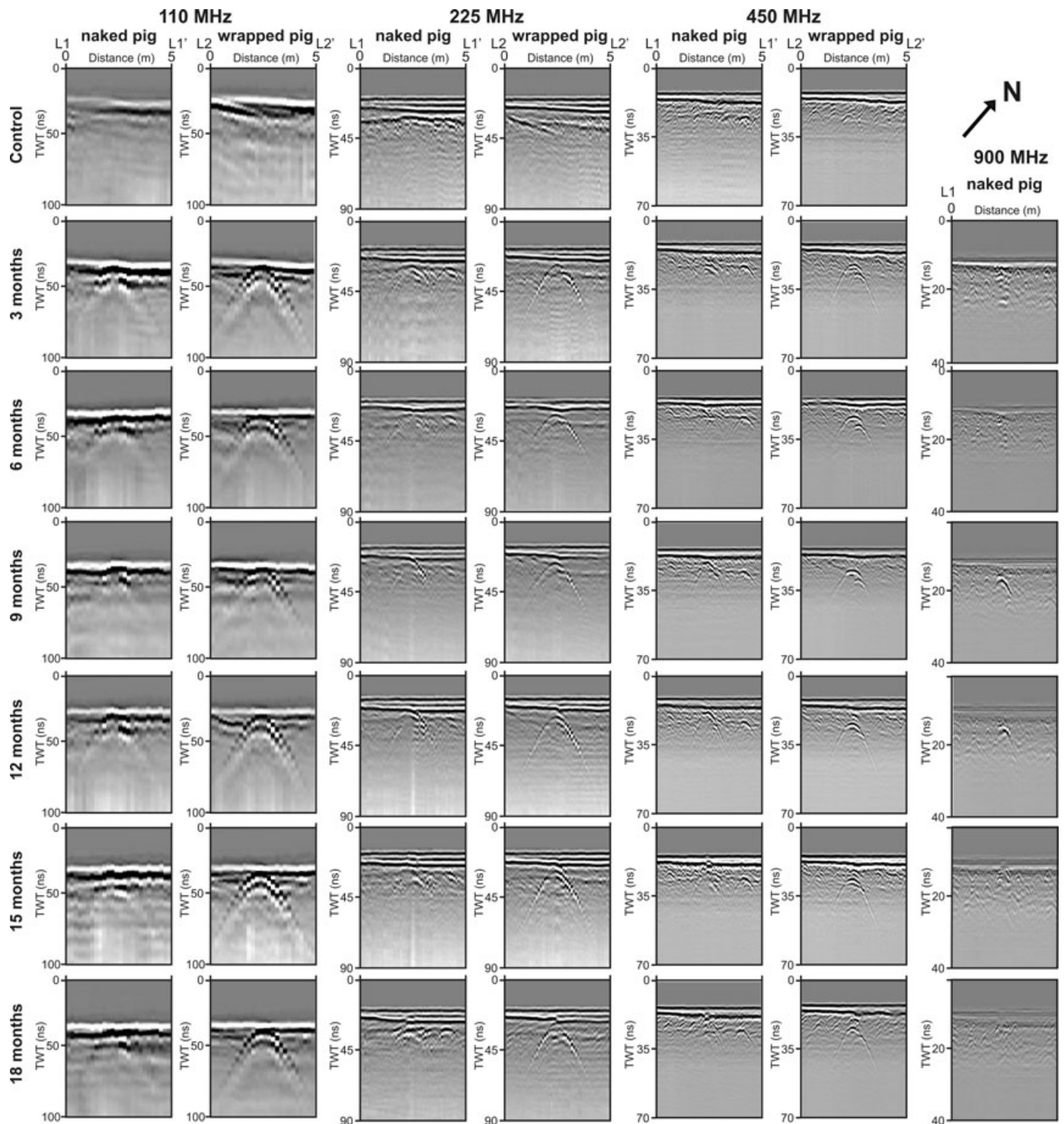


FIG. 9—(A) Key sequential processed 110-, 225-, 450-, and 900-MHz dominant frequency ground-penetrating radar (GPR) profiles that bisect the naked and wrapped pig “graves,” respectively (see Fig. 2A for location) that include control profiles and data collected from 0 to 18 months after burial. (B) Key sequential processed 110-, 225-, 450-, and 900-MHz dominant frequency GPR profiles that bisect the naked and wrapped pig “graves,” respectively (see Fig. 2A for location) that include data collected from 21 to 36 months after burial. Continued.

amplitude compared to background values. In terms of optimally configuring fixed-offset resistivity equipment if the likely depth of burial is unknown, modern versions (e.g., 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 datum is collected

and trace sample spacing could still be comparatively small so that any potential loss in resolution is minimized. 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.

Second, could GPR surveys successfully locate both simulated clandestine burials throughout the 3-year monitoring period? And

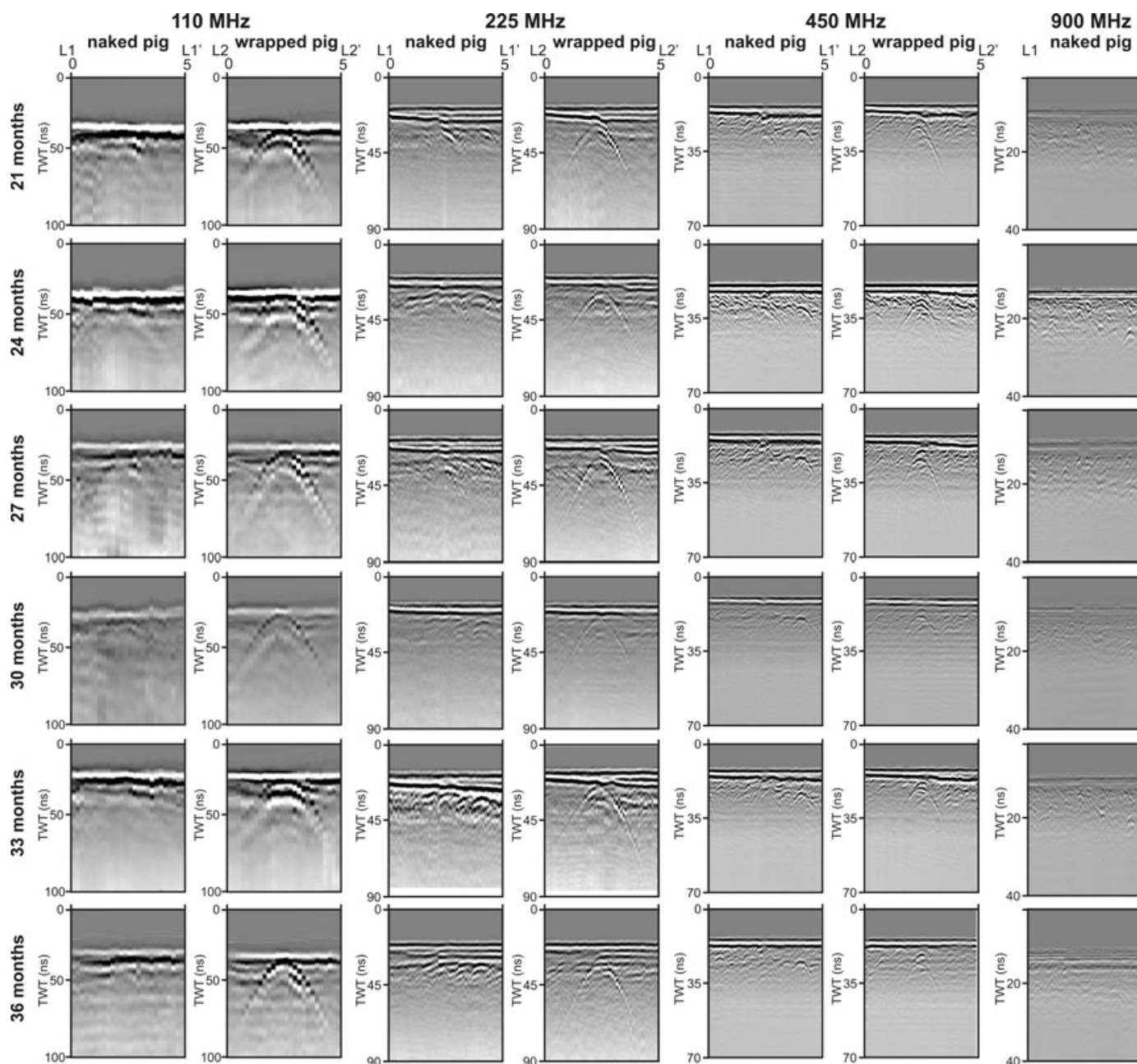


FIG. 9—Continued.

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 of 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 nontarget 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 (52) 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

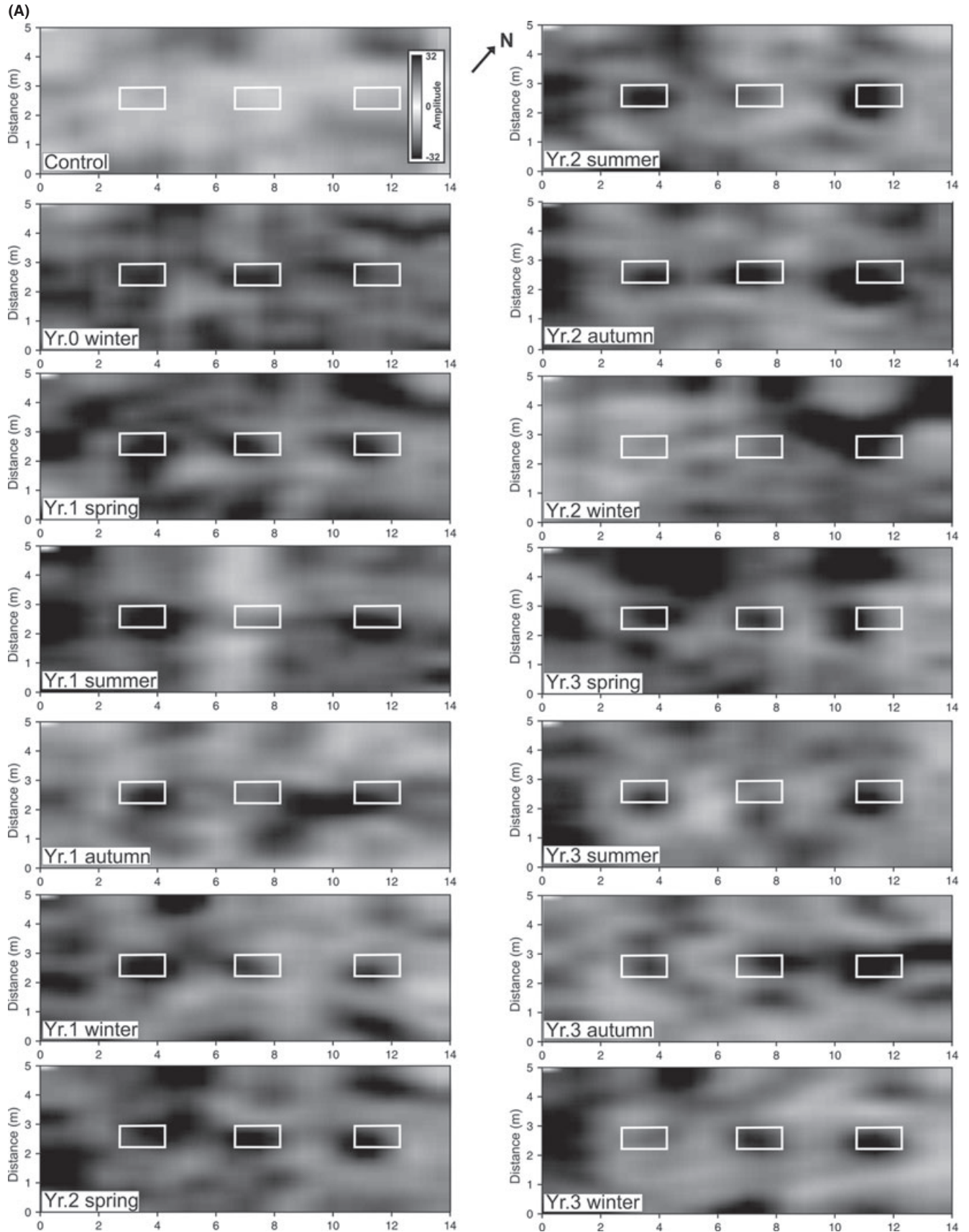


FIG. 10—(A) The 110-MHz frequency, quarterly ground-penetrating radar (GPR) processed “time-slice” datasets. Common amplitude scale shown in control dataset. Dotted squares indicate “graves” (see Fig. 2A for location). (B) The 225-MHz frequency, quarterly GPR processed “time-slice” datasets. Common amplitude scale shown in control dataset. Dotted squares indicate “graves” (see Fig. 2A for location). (C) The 450-MHz frequency, quarterly GPR processed “time-slice” datasets. Common amplitude scale shown in control dataset. Dotted squares indicate “graves” (see Fig. 2A for location).

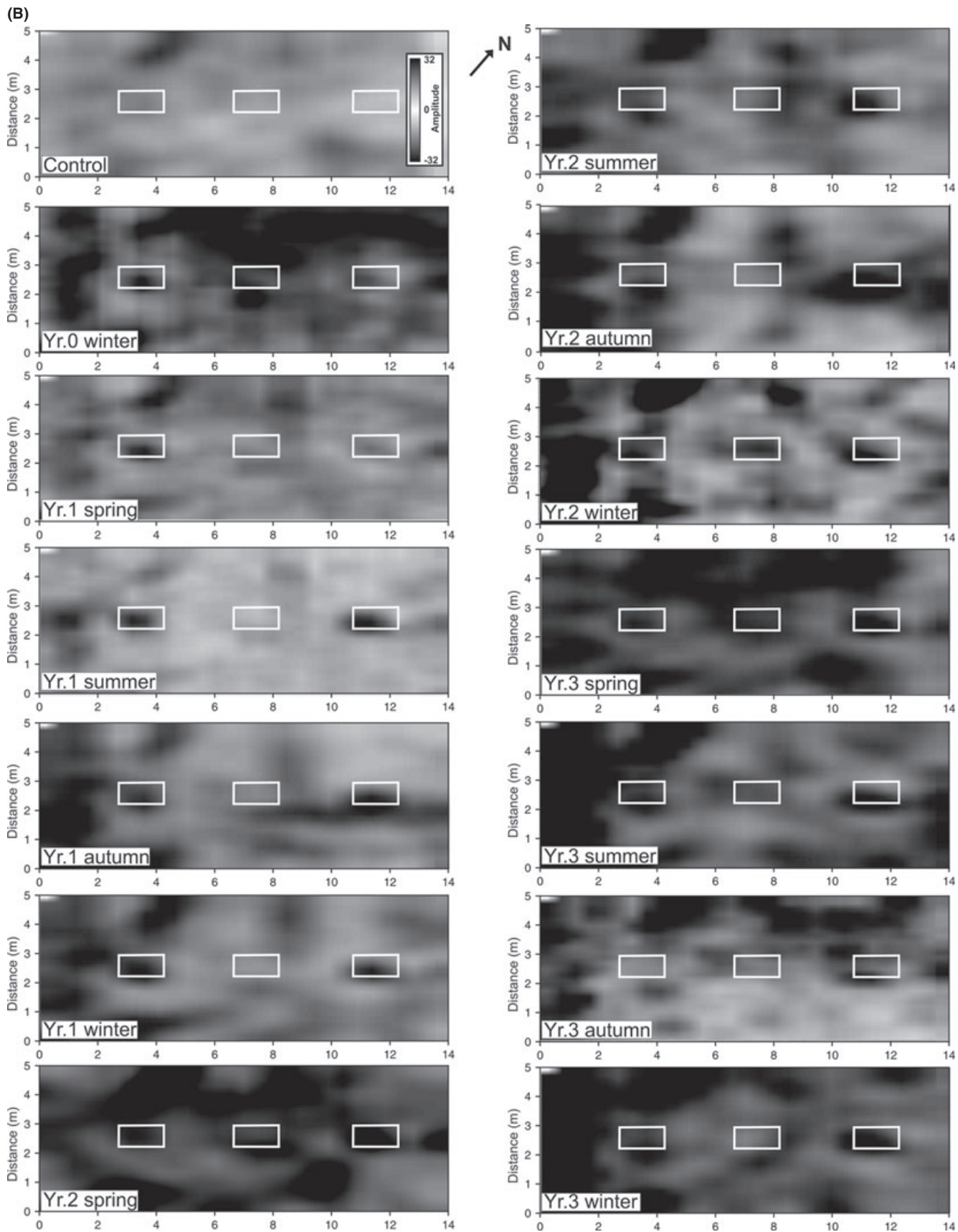


FIG. 10—Continued.

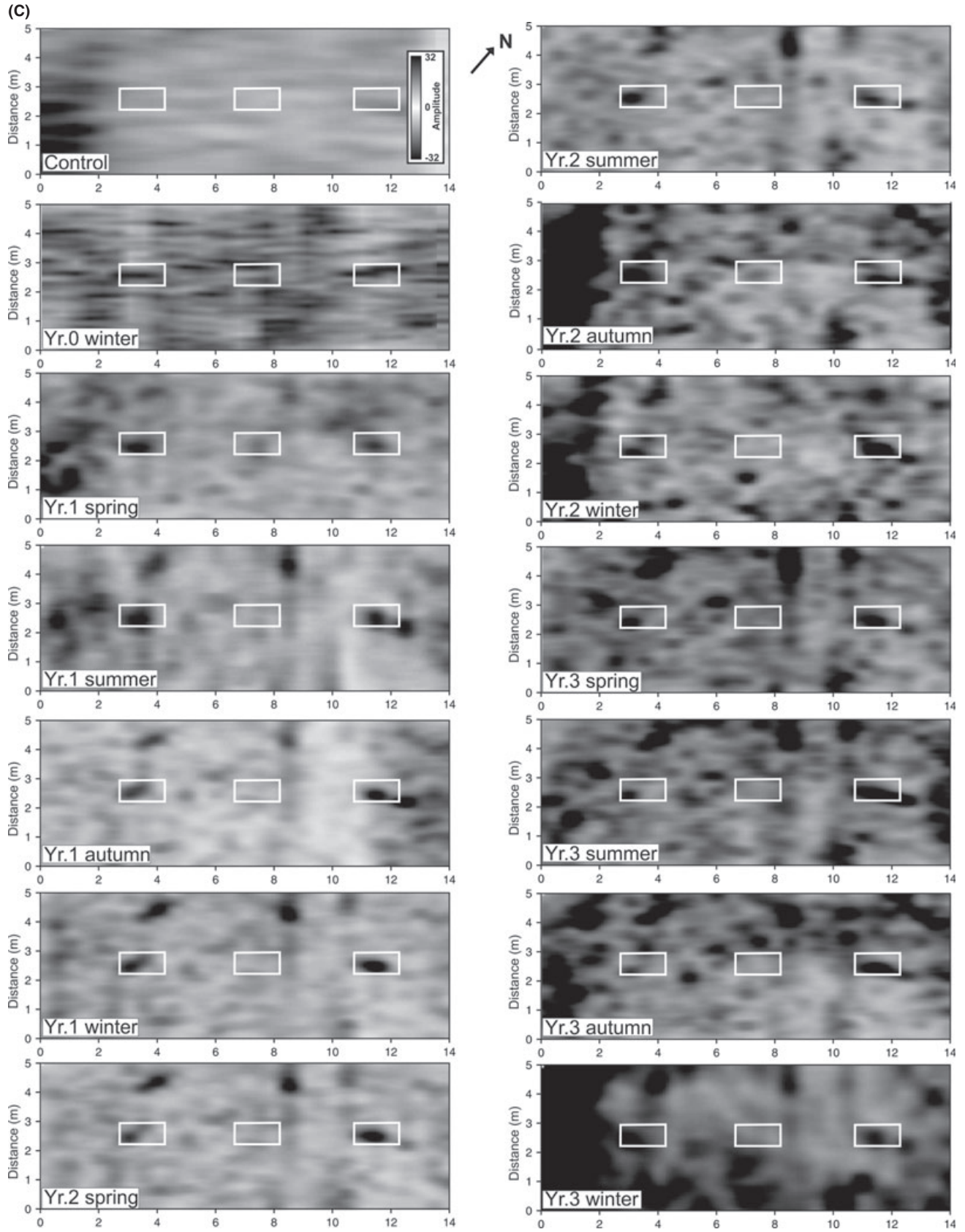


FIG. 10—Continued.



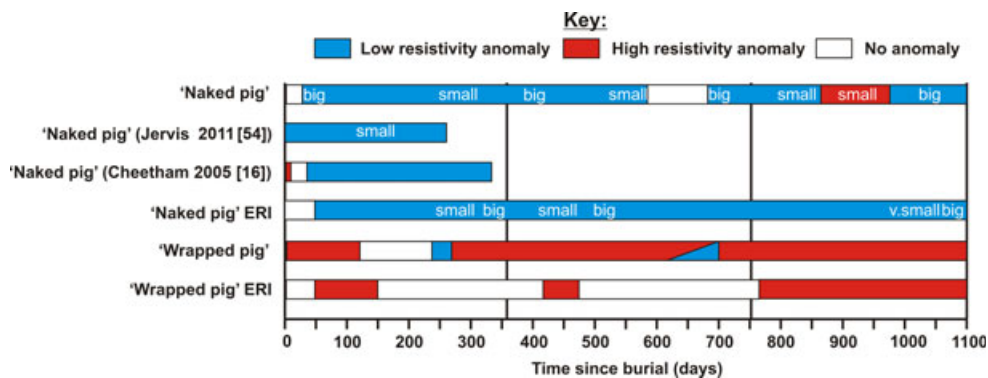


FIG. 11—Graphical timeline (vertical lines indicate time in years) showing resistivity changes over simulated graves. Relative anomaly sizes are also noted. Two other named studies are shown for comparison. All graves were buried at 0.5 m bgl.

horizontal time-slices for the frequencies trialled showed generally good results throughout, with the wrapped cadaver again being spatially larger in extent 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 nontarget 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.

Third, when was the optimal time (both up to 3 years postburial 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; that is, 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 favorable GPR survey results over much older burials in different ground conditions (e.g., [14,21,28]). 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 Clark (53) who undertook time-lapse resistivity surveys over U.K. Roman fortification defense ditches. This study can partly quantify the reasons for the preferred resistivity winter survey season by analyzing 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 standard deviation values and high summer/autumn standard deviation values repeating each year during the 3-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 nonuniform manner for this study site. Thus, the “noise” present within the

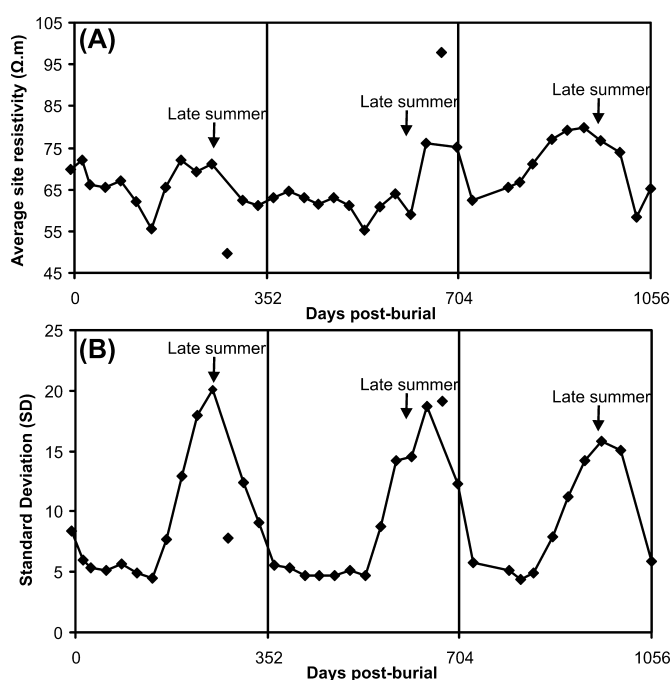


FIG. 12—Summary analysis plots of monthly fixed-offset resistivity data collected during this study. (A) Average resistivity values and (B) standard deviations (SD) for each survey. Note SD values are highest in late summer. Two survey outliers (collected at 280 and 672 days after burial) are shown but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

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 standard deviation survey outliers acquired on days 280 and 672 post-burial (Fig. 12B) that did not fit the other data set 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).

Fourth, 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 Powell (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, for example, 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 0.5-m probe spaced, fixed-offset resistivity survey, which would therefore resolve deeper graves than the 0.5-m bgl graves investigated in this study. Finally collecting multiple 2D ERI profiles would allow 3D data sets to be generated that could better locate and define grave positions as (42) showed using this technique on a mass grave search.

*Fifth, 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 simulated forensic geophysical study (30) 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 vs. ~31 kg for this study and [30] 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 GPR time-lapse simulated burial study (23) also concludes that pig cadavers were easier to locate in sandy rather than clay-rich soil types. Therefore, it is suggested that resistivity surveys would be more favorable 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 (30) which would make identifying anomalous area in GPR surveys in this environment problematic.

*Sixth, what was important to do when processing electrical resistivity data sets?* From reviewing this study fixed-offset resistivity survey results, initial recommendations were to be careful when “de-spiking” data sets 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 data set (~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 data sets; otherwise, site trends would potentially have masked the anomaly location(s). It is important to point out that detrending resistivity data sets 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 (16,18), then these boundaries will commonly produce high-resistivity values because of 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 utilize cross-model constraints for the time-lapse inversion and to implement a user-defined (rather than default) linear scale for the percent change in resistivity when displaying the differential images. This was needed to reduce data uncertainties/artifacts 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 data sets acquired. This was a similar methodology used by Jones et al. (46) in a 3-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, normalization should not be needed for an active forensic geophysical search.

*Seventh, what was important to do when processing GPR survey data sets?* 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 (23,24,52). Horizontal time-slices were also generated of the 110-, 225-, and 450-MHz dominant antennae frequency data sets, 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 data sets 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 forensic search in a mountainous environment (19) and the simulated study in an urban garden environment (25). 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 (13,17,18,29,49,54,55), 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 forensic resistivity search (18). Once anomalous geophysical areas within the survey area are identified, these should be prioritized 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, and invasive probing.

## 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 owing 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, because of 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 that need to be processed before being interpreted. However, in more heterogeneous ground, or where the time since burial is significant, that is, 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 nontarget 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 (32); details analysis of 6 months of samples using inductively coupled plasma mass spectrometry.

Further analysis of the geophysical data will also be undertaken both to determine whether there are diagnostic GPR signal spectra for clandestine burials versus background signals and to determine whether both GPR and resistivity data sets 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, to determine whether 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, U.K., 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 analogs, 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, U.S.A.

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