



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

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3 1 **Long-term geophysical monitoring of simulated clandestine graves using**
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5 2 **electrical and Ground Penetrating Radar methods: 4-6 years after burial**
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19 **ABSTRACT**

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

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36 **Keywords:** forensic science; forensic geophysics; clandestine grave; monitoring;

37 electrical resistivity; ground penetrating radar; conductivity

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3 40 Forensic search methods vary widely, for example, in the UK a search strategist is
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5 41 usually involved in a case at an early stage to decide upon the highest probability of
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7 42 search success [1], whereas in other countries a search may not be methodical,
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9 43 investigations may not be standardised and a variety of techniques are undertaken,
10
11 44 depending upon local experience [2]. Metal detector search teams [3-5] and specially
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13 45 trained search dogs [5-7] are both commonly used during either initial investigations
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15 46 or as part of a phased sequential programme.
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21 48 Forensic investigators have been increasingly using geoscientific methods to aid in
22
23 49 civil or criminal forensic investigations, predominantly to assist search teams or for
24
25 50 trace evidence purposes [8-11]. One key and high-profile 'target' for forensic search
26
27 51 teams to detect and locate is human remains buried within clandestine graves [1,5,12].
28
29 52 These searches generally start from large-scale remote sensing methods [13-14], aerial
30
31 53 and ultraviolet photography [10,15], thermal imaging [16], to ground-based
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33 54 observations of vegetation changes [4], surface geomorphology changes [17], soil
34
35 55 type [1] and depositional environment(s) [10], near-surface geophysics [11],
36
37 56 diggability surveys [1] and probing of anomalous areas [18,19] before topsoil removal
38
39 57 [4], and finally controlled excavation and recovery [5,15,20]. A typical search will
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41 58 only use a few of these techniques, depending on the circumstances of each case
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44 59 (Colin Hope, *pers. comm.*).
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50 61 Near-surface geophysical methods rely on there being a detectable physical contrast
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52 62 between the target and the background (or host) materials (see [21]). Near-surface
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54 63 geophysical surveys have been used to try and locate clandestine graves in a number
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56 64 of reported criminal search investigations [3,5,22-32]. Geophysical surveys collected
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3 65 over simulated burials have been undertaken in order to collect control data (e.g. [33-
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5 66 37]. These studies have shown that the resulting geophysical responses could be well
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7 67 predicted, although responses seem to vary both temporally after burial and between
8
9 68 different study sites. A few studies have also collected repeat (time-lapse)
10
11 69 geophysical surveys over controlled experiments (e.g. [26,38-44]), which have
12
13 70 documented temporal changes in geophysical responses over their study periods.
14
15 71 However, uncertainties still remain over what and how long temporal variations occur
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17 72 in geophysical surveys after burial, with study survey sites needing to be fully
18
19 73 characterised (e.g. geologically and climatologically) to allow comparisons with other
20
21 74 studies or indeed for active forensic cases. Documenting temporal changes is
22
23 75 important as geophysical responses from recent clandestine burials are known to vary
24
25 76 more than archaeological graves. Potential reasons for this could be the temporal
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27 77 changes in grave soil characteristics, decomposition products [45], climatic variations,
28
29 78 soil moisture content [46] and other site specific factors (see [11]).
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36 80 This study continued the systematic assessment of the changing geophysical response
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38 81 of simulated clandestine graves during four to six years after burial. Geophysical
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40 82 survey results from zero to three years after burial were published in [47]. A
41
42 83 clandestine grave was defined in this study as an unrecorded burial that has been
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44 84 hand-excavated and dug <1 m depth below ground level (bgl). It should be noted that
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46 85 geophysical results will vary depending upon the depth of burial and indeed on local
47
48 86 soil type as [11] reviews. The discovered graves published in [15,48] were usually
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50 87 rectangular in plan-view, mostly hurriedly hand dug using garden implements and
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52 88 usually just large enough to deposit the victim before being back-filled with excavated
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54 89 soil and associated surface debris. [48] also detailed that almost half of the 87
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3 90 documented U.S. cases were either clothed or encased in material (plastic or fabric),
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5 91 so the authors decided to use two end member scenarios for this study; namely one
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7 92 burial containing a *naked* cadaver and another containing a cadaver *wrapped* in a
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10 93 tarpaulin. It is, however, emphasised that these obviously do not represent all types of
11
12 94 potential style of burial with [42] considering other scenarios.
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16 96 There are many potential near-surface geophysical search techniques that could be
17
18 97 utilised to search for clandestine graves that the [47] monitoring paper summarises;
19
20 98 this ongoing study has concentrated on collecting electrical resistivity (fixed-offset
21
22 99 and Electrical Resistivity Imaging 2D profiles) and Ground Penetrating Radar (110 –
23
24
25 100 900 MHz frequency 2D profiles. Resistivity surveys showed consistent low
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27 101 anomalies, compared to background values, for a naked burial, in contrast with the
28
29 102 wrapped burial which had smaller and varied low/high anomalies and was thus harder
30
31 103 to locate [47]. Analyses of decompositional fluids showed highest conductivity
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33 104 values, compared to background soilwater, was ~1 year to ~2 years after burial before
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35 105 subsequently decreasing [47]. GPR surveys finally showed low frequency antennae
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37 106 were consistently optimal for target detection [47].
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42 108 The aims of this continued four to six year geophysical monitoring study of different
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44 109 simulated burial style clandestine burials were to answer some basic questions posed
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46 110 by forensic search teams. Appropriate site data (rainfall, temperature, soil and 'grave'
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48 111 water conductivities) were also continued to be simultaneously collected in order to
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50 112 allow comparisons with other research studies and criminal search investigations.
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52 113 Basic forensic search questions which were continued to be addressed by this study
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55 114 were:
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3 115 **A)** Could twin electrode (fixed-offset) and electrical resistivity imaging surveys still
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5 116 successfully locate both simulated clandestine burials beyond three years after
6
7 117 burial? And if so, how long were they geophysically detectable for?
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10 118 **B)** Could single profile GPR surveys successfully locate both simulated clandestine
11
12 119 burials throughout the four to six year post-burial monitoring period? If this was
13
14 120 the case, which dominant frequency antenna was optimal to detect them?
15
16 121 **C)** When was the optimal time (both up to six years post-burial and seasonally) to
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18 122 undertake a forensic GPR or electrical resistivity geophysical search survey?
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21 123 **D)** When should a forensic geophysical survey be undertaken in a six year search
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23 124 scenario?
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3 126 **Methodology**
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7 128 *Study site*
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11 130 The chosen controlled test site was located on Keele University campus, ~ 200 m

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14 131 above sea level, close to the town of Newcastle-under-Lyme in Staffordshire, UK.

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16 132 The local climate is temperate, which is typical for the UK [49]. The study site was a

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18 133 grassed, small rectangular area (~25 m x ~25 m), surrounded by small deciduous trees

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20 134 (Fig. 1). The geophysical survey area measured 5 m x 14 m and sloped by

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22 135 approximately 3° from northwest to southeast. Within this area were the ‘naked pig’

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24 136 grave, the empty grave and the ‘wrapped pig’ grave emplaced in sandy loam soil (Fig.

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26 137 1). [47] provides other relevant background site information.
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31 139 The test site was located ~200 m from the Keele University weather observation

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33 140 station, which continually measured daily rainfall and air and ground temperatures as

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35 141 well as having soil temperature probes at 0.1 m, 0.3 m and 1.0 m below ground level.

36
37 142 Figure 2 shows a monthly summary of the total rainfall and average temperature data

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39 143 over the monitoring period with temperature data for the zero to three year monitoring

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41 144 study also shown for comparison. The local weather station data showed that total

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43 145 monthly rainfall during the four to six year study period ranged from 2.6 mm to 152.2

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45 146 mm, with an overall monthly average of 64.7 mm, the same as for the zero to three

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47 147 year monitoring period [47]. Average monthly air temperatures ranged from -1.2 °C

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49 148 to 12.8 °C, with an overall monthly average of 5.5 °C, 3.2 °C colder than for the zero

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51 149 to three year monitoring period (Fig. 2). However, note at 0.3m bgl the average

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53 150 temperature was 10.2 °C for the four to six year monitoring period and 9.8 °C for the
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3 151 0-3 year monitoring period [47]. Accumulated Degree Day (ADD) data (see [50] for
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5 152 background) detailed in Table 1 quantified these temperature differences.
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10 154 **FIG. 1. -position**

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13 156 **FIG. 2. -position**

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15 158 *Simulated graves*

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23 160 Five simulated graves were created at the site (Fig. 1A). Three of the graves were
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25 161 used for the repeat geophysical surveys, whilst ground water samples were collected
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27 162 at regular intervals from both the fourth grave and a separate control site situated ~10
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29 163 m upslope away from the graves (Fig. 1E-F), both of the soilwater sampling sites
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31 164 being outside the geophysical survey area (Fig. 1A). Of the three simulated graves
32
33 165 geophysically surveyed, one contained a naked pig carcass, one contained a carcass
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35 166 wrapped in woven PVC tarpaulin and the third was an empty grave to act as a control
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37 167 (Fig. 1). Pig cadavers are commonly used in such monitoring experiments as they
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39 168 comprise similar chemical compositions, size, tissue:body fat ratios and skin/hair type
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41 169 to humans [51,52]. The grave emplacement procedure was described in [47].
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47 171 *Bulk ground water conductivity data collection*

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52 173 Ground water sample lysimeters were emplaced both within a grave containing a pig
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54 174 carcass outside the geophysical survey area and a further lysimeter ~10 m from the
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56 175 survey area to act as control (Fig. 1). The lysimeter emplacement and regular sample
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3 176 collection (Table 1) and analysis procedures used in this study were the same as for
4
5 177 the initial three year monitoring period and are described in [47]. The only change
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7 178 was the sample frequency with samples collected at approximately three-monthly
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9 179 seasonal intervals during the four to six year monitoring period due to limited monthly
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11 180 changes observed in the zero to three year monitoring period [47] and survey time
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13 181 constraints (Table 1).
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17
18 **TABLE 1.**
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23 *Near surface geophysical data collection & processing*
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27 187 Twin electrode (0.5 m fixed-offset) resistivity surveys were conducted at three
28
29 188 monthly intervals over the geophysical survey area (Fig. 1A-B) during the four to six
30
31 189 year monitoring period (Table 1). Data was collected using the RM15 (Geoscan™
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33 Research) resistivity meter on a 0.25 m by 0.25 m grid with remote probes placed on
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35 190 the same position 17 m from the survey area for consistency. Subsequent data
36
37 191 processing methodology was the same as detailed in [47].
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43 194 A 2D Electrical Resistivity Imaging (ERI) survey line orientated SW-NE (Fig. 1A-B)
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45 195 was surveyed at approximately three-monthly intervals (Table 1). 32 electrodes were
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47 196 placed every 0.5 m along the 15.5 m long survey profile that bisected all three graves
48
49 197 (Fig. 1A). Geophysical survey collection using a Campus™ TIGRE system and
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51 198 subsequent inversion using Geotomo™ Res2Dinv v.355 software used in this study
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53 199 were the same as for the initial three year monitoring period and are described in [47].
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3 201 Due to the variable results of horizontal time slices that GPR data generated in the
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5 202 zero to three year monitoring survey period (see [47]), 2D GPR profiles were only
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7 203 collected on two profiles within the survey area that bisected the two simulated graves
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9 204 with pigs present (Fig. 1A) at approximately three-monthly intervals (Table 1). GPR
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11 205 data collection using the PulseEKKO™ 1000 equipment utilised 110 MHz, 225 MHz,
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13 206 450 MHz and 900 MHz dominant frequency antennae, with radar trace spacings being
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15 207 0.2 m, 0.1 m, 0.05 m, and 0.025 m, respectively, using 32 “stacks” to increase the
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17 208 signal-to-noise ratio and for all data sets for consistency purposes. Subsequent data
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19 209 processing were the same as for the initial three year monitoring period and are
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21 210 described in [47].
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3 213 **Results**
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7 215 Table 1 qualitatively summarises the respective geophysical anomaly visibilities in
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9 216 survey results based on [42] methodology of: *None*, *Poor*, *Good* and *Excellent*. A
10
11 217 score of *None* indicated the respective grave was not detected, with a score of *Poor*
12
13 218 showed a slightly discernible geophysical anomaly at the grave location. A score of
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15 219 *Good* demonstrates a clear geophysical anomaly that would be discernible in the field
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17 220 during a geophysical survey and a score of *Excellent* demonstrates a clearly
18
19 221 discernible and prominent anomaly at the grave location.
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22 222
23 223 *Bulk ground water conductivity*
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27 224
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29 225 Background soilwater conductivity measurements demonstrated that background
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31 226 values were consistent over the three year monitoring period (averaging 355 ± 0.1
32
33 227 $\mu\text{S}/\text{cm}$ with 40 SD) that was comparable to the zero to three year monitoring period
34
35 228 (averaging $444 \pm 0.1 \mu\text{S}/\text{cm}$). However, the pig leachate conductivity continued to
36
37 229 reduce during year four (Fig. 3A), varying from $6,670 \pm 0.1 \mu\text{S}/\text{cm}$ (1,099 days after
38
39 230 burial) down to consistent and comparable background values of $356 \pm 0.1 \mu\text{S}/\text{cm}$
40
41 231 after 1,670 days of burial to the end of the monitoring period. Pig leachate
42
43 232 conductivity changes during the first three years of burial are reported in [47].
44
45 233 Leachate values in this study could be divided into two clear groupings of
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47 234 conductivity against post-burial days; 840-1,670 burial days (which included some
48
49 235 data from the third year of monitoring) and 1,670 burial days to the end of the survey
50
51 236 period respectively (Fig. 3A). The first data grouping had a decreasing regression line
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53 237 against burial days with a reasonable fit ($R^2 = 0.88$), with the second data grouping
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3 238 having a flat regression line, albeit with a relatively poor correlation ($R^2 = 0.47$) due
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5 239 to its flat nature, evidencing that pig leachate conductivity was consistently at
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7 240 background soilwater values (Fig. 3A).
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11 242 **FIG. 3. - position**

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16 244 Site temperature variation could be removed from raw conductivity values as
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18 245 discussed in [47 Pringle et al. 2012 jfs] by weighting each day by its average daily
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20 246 temperature and then giving each day after burial an accumulated degree day (ADD)
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22 247 following standard methods [50]. This study still had the advantage of having
23
24 248 temperature probe measurement data available from the actual mid-cadaver depth
25
26 249 (~0.3m bgl) from the nearby meteorological weather station, instead of using average
27
28 250 air temperatures (Fig. 2). This again allowed the separation of two data groupings
29
30 251 with two linear regression correlations to be generated of conductivity against ADD,
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32 252 with similar fits to those generated against post-burial days (R^2 values of 0.86 and
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34 253 0.57 respectively), see Fig. 3B.
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40 255 Twin electrode (*fixed-offset*) resistivity

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45 257 Bulk ground resistivity surveys acquired over the four to six year monitoring study
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47 258 period were again remarkably consistent, with average fixed-offset survey resistance
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49 259 values of 63.6 Ω (with 47.0 Ω minimum and 99.4 Ω maximum values respectively)
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51 260 (compared to an average of 67.1 Ω for zero to three years), after de-spiking data (only
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53 261 averaged 1.6 anomalous 'spike' per survey). The three monthly processed fixed-
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3 262 offset resistivity surveys are graphically shown in Figure 4 (see Fig. 1A for ‘grave’
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5 263 locations) and summarised in Table 1.
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9 265 As found in the zero to three year monitoring datasets, the empty grave which acted as
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11 266 control could not be geophysically detected throughout the survey period (green boxes
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13
14 267 in Fig. 4). The naked pig grave (red boxes in Fig. 4) was anomalously temporally
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16 268 variable throughout the four to six year monitoring period, mostly comprising a small
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18 269 ($<0.6 \text{ m}^2 \text{ SD}$) amplitude mixed low/high anomaly, when compared to background
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20
21 270 values (Fig. 4 and Table 1). It only comprised a large anomaly with a low resistivity
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23 271 (coloured blue) in the winter Year 4 dataset that was consistently observed in the zero
24
25 272 to three year monitoring datasets (see [40] and Table 1). In contrast, the wrapped pig
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27 273 grave (blue boxes in Fig. 4) showed predominantly a large ($>0.6 \text{ m}^2 \text{ SD}$) amplitude
28
29 274 high resistivity anomaly (coloured red/white), when compared to background values,
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31 275 that was mostly *Good* to *Excellent* rating and appeared to have increased in size from
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33 276 the zero to three year monitoring dataset immediately after burial (see [47] and Table
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35 277 1).
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41 279 **FIG. 4. – position**

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45 281 *Electrical resistivity imaging (ERI)*
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49 283 After de-spiking data, electrical resistivity imaging surveys acquired over the four to
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51 284 six year monitoring study period were also again consistent, with average ERI six ‘n’
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53 285 level survey resistivity values of $197.0 \Omega \cdot \text{m}$ with $106.0 \Omega \cdot \text{m}$ minimum and $318.9 \Omega \cdot \text{m}$
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55 286 maximum respectively (compared to an average of 161.8Ω for zero to three years) A
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3 287 summary of the 2D ERI profiles collected is graphically shown in Figure 5 (see Fig.
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5 288 1A for profile location) and summarised in Table 1. An average inversion model
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7 289 error (RMS) of 2.1 (with 1.2 minimum and 5.1 maximum) after five iterations again
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9 290 indicated a very good model inversion fit to the collected resistivity values (compared
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11 291 to a RMS of 2.82 for zero to three years),.

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16 293 The empty grave (marked in Fig. 5) again could be detected throughout the survey
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18 294 period, although, in contrast to the zero to three year monitoring period, it had
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20 295 consistently higher resistivity values, when compared to neighbouring regions (Fig.
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22 296 5). The naked pig grave was again generally detectable as a consistent *Good* rated
23
24 297 anomalous low, when compared to background values up to the end of year five,
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26 298 although thereafter it was difficult to resolve from neighbouring regions (Fig. 5 and
27
28 299 Table 1). The wrapped pig grave was surprisingly detectable as a large high *Good*
29
30 300 rated resistivity anomaly, when compared to background values, although the
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32 301 anomaly was relatively smaller in the summer and autumn of year's four and five
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34 302 (Fig. 5). In the zero to three year monitoring survey the high resistivity anomaly was
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36 303 relatively smaller (see [47] and Table 1).

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43 305 **FIG. 5. - position**

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47 307 *Ground Penetrating Radar (GPR)*

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52 309 The 2D GPR profiles acquired throughout the four to six year monitoring survey
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54 310 period are shown in Figure 6A and 6B (see Fig. 1A for profile locations) and
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56 311 summarised in Table 1. The 110 MHz dominant frequency 2D profiles showed the
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3 312 wrapped pig grave could still be consistently and clearly identified by a strong *Good*
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5 313 to *Excellent* rated hyperbola throughout the survey period (except for year 5 summer),
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7 314 although there was a continual reduction in reflection amplitudes. This was in
8
9 315 contrast to the naked pig grave which was either not detectable or at best produced a
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11 316 *Poor* rated hyperbola throughout the survey period (see Fig.6A and 6B and Table 1).
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13 317 There were no clear hyperbolae other than those associated with the target graves
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15 318 within these 2D profiles.
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20 320 The 225 MHz dominant frequency 2D profiles still showed the wrapped pig grave
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22 321 could be clearly identified by an obvious *Good* to *Excellent* rated hyperbola
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24 322 throughout the four to six year monitoring survey period, although there was also a
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26 323 continual reduction in reflection amplitudes (see Fig.6A and 6B). The second,
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28 324 slightly deeper reflector that was first resolved after 15 months of burial within the
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30 325 wrapped pig grave (see [47]) was still present in this dataset. The naked pig grave
31
32 326 was given a *Poor* to *None* rating of hyperbola anomaly throughout the four to six year
33
34 327 monitoring survey period although it was possible to detect in the autumn and winter
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36 328 data of year 4 (Fig. 6A/B). As per the zero to three year monitoring survey results
37
38 329 [47], there were other, smaller hyperbolae present in the naked pig profiles that were
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40 330 not associated with the target. This would have made it difficult to identify the target
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42 331 grave if the position was not known. However, note they may have been detected if
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44 332 data were collected orthogonally to the primary survey line orientation or indeed if
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46 333 time slices were generated (although the zero to three year survey time slice data
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48 334 detailed in [47] was poor).
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3 336 The 450 MHz dominant frequency 2D profiles showed the wrapped pig grave could
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5 337 be identified by a *Good to Excellent* rated hyperbola throughout the four to six year
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7 338 monitoring survey period, but this had a consistently low amplitude (see Fig. 6A and
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9 339 6B and Table 1). The second, slightly deeper hyperbola observed after 3 months of
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11 340 burial was still present during this survey period. The naked pig grave was rated as
12
13 341 *Poor to None rated* detectable as a hyperbola throughout the four to six year
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15 342 monitoring period. There were again numerous other, smaller hyperbolae present in
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17 343 both profiles that were not associated with the target grave which would have made it
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19 344 difficult to identify the target grave if the position was not known. These may, again
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21 345 have been detected if data were collected orthogonally to the primary survey line
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23 346 orientation or indeed if time slices were generated (although the zero to three year
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25 347 survey time slice data detailed in [47] was again poor).
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32 349 The 900 MHz dominant frequency 2D profiles was rated *Poor to None* rated so was
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34 350 difficult to identify the naked pig grave throughout the four to six year monitoring
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36 351 period (see Fig. 6A and 6B). There were numerous other, smaller hyperbolae present
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38 352 which would also have made it difficult to locate the target grave, although orthogonal
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40 353 surveys may have been successful.
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46 355 **FIG. 6(A).**

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49 357 **FIG. 6(B).**

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361 **Discussion**

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

371

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

375 From the results of this long-term study, the answer was, it still depends on the burial
376 style. The fixed-offset electrical resistivity surveys showed that a naked cadaver(s)
377 has a good chance of being located up to 2.5 years after burial (see Table 1 and [47]),
378 due to the highly conductive grave fluid' producing a consistent low resistance
379 geophysical anomaly when compared to background site resistance values (Fig. 3).

380 This agrees with other resistivity studies over simulated clandestine burials with

381 similar monitoring time periods (see [26,52]. Recent collaborative research

382 comparing the same monitoring experiment on three different University sites in

383 contrasting soil types has evidenced that conductivity measurements of grave fluids

384 could date the burial interval of a discovered clandestine grave in the field if a

385 conductivity meter was available and enough grave fluid was present (see [45]).

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3 386 However, this study showed that a naked cadaver would be very difficult to detect
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5 387 using fixed-offset electrical resistivity surveys after only four years of burial (Fig. 4)
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7 388 and using ERI surveys after five years of burial (Fig. 5) respectively. The majority of
8
9 389 the grave fluids (other than that held by capillary pressure) would migrate away from
10
11 390 the cadaver and potentially result in a geophysical anomaly not being over the target,
12
13 391 and hence the subsequent search excavation team not finding the target, which would
14
15 392 be especially problematic in surveys within significant topographic variation (see
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17 393 [1,30]. In contrast, the wrapped or clothed cadaver(s) essentially largely isolated the
18
19 394 target and its conductive grave fluids from the surrounding soil, giving a potential
20
21 395 barrier to electrical current. There was therefore a small and temporally varying high
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23 396 resistance anomaly, with respect to background site resistance values, identified over
24
25 397 the wrapped target location in the zero to three year monitoring data (see [47]), the
26
27 398 varying nature suggested to be caused by some leaking of grave fluids into the
28
29 399 surrounding soil. However, this paper detailing the four to six year monitoring data
30
31 400 showed a consistent large high resistance anomaly, when compared to background
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33 401 site resistance values, to be present in both the fixed-offset and ERI electrical
34
35 402 resistivity datasets over the wrapped cadaver (see Figs. 4 and 5), this consistency
36
37 403 presumably due to most grave fluid at this time period being largely absent from the
38
39 404 survey area. Note that wrapping a body in plastic or clothing has also been reported
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41 405 by others to slow decomposition [53] and inhibit micro-organism activity [51] which
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43 406 therefore suggests a clandestinely buried body may be identifiable for longer if
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45 407 wrapped in woven PVC tarpaulin as compared to naked.
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53 409 Using all the resistivity datasets collected in the six year monitoring period, a
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55 410 graphical time-line diagram has been generated to show temporal resistivity anomaly
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3 411 variations (Fig. 7). In terms of optimally configuring fixed-offset resistivity
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5 412 equipment if the likely depth of burial is unknown, modern versions (eg. the
6
7 413 Geoscan™ RM-15 used in this study) have the capability to collect and digitally
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9 414 record fixed-offset resistivity data at a variety of probe spacings almost
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11 415 simultaneously at each sampling position (see [54] for forensic resistivity dataset
12
13 416 examples). This would therefore not significantly add to survey time if more than one
14
15 417 probe spacing data is collected and trace sample spacing could still be comparatively
16
17 418 small so that any potential loss in resolution is minimised. The forensic resistivity
18
19 419 survey results in this paper are in sandy loam soil, with good forensic resistivity
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21 420 survey results also reported in coastal sand [36], chalky [26] and black earth [54] soil
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23 421 types respectively, but relatively poor results in coarse pebble soil types [54].
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30 **FIG. 7. - position**

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34 425 *B) Could single profile GPR surveys successfully locate both simulated clandestine*
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36 426 *burials throughout the four to six year monitoring period? And which dominant*
37
38 427 *frequency antenna was optimal to detect them?* From the results shown in this four to
39
40 428 six year monitoring study, the naked cadaver was not able to be detected on 2D GPR
41
42 429 transverse profiles using either the 110 MHz or 900 MHz dominant frequency
43
44 430 antennae and was only poorly detectable by the 225 MHz dominant frequency
45
46 431 antennae in the autumn to winter datasets (Fig. 6A/B). This was in contrast to the
47
48 432 zero to three year monitoring period [47] and other studies undertaken on [47]
49
50 433 timescale (e.g. see [38,39,42]). The naked cadaver, however, was detectable as a
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52 434 deeper ½ hyperbolic reflection event in the 450 MHz 2D transverse profiles although
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54 435 this did not have high amplitudes (Fig. 6A/B). In contrast, the wrapped cadaver was
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3 436 detectable on 2D GPR profiles using all the frequencies trialled, namely the 110, 225
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5 437 and 450 MHz dominant frequency antennae (the 900 MHz antennae was not used
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7 438 over this grave, but it is believed that the grave could have been detected with this
8
9 439 frequency based on the other frequency data). This was presumably still due to the
10
11 440 wrapping surface allowing stronger GPR reflections to be obtained, with the
12
13 441 decomposing naked cadaver attenuating a greater proportion of the GPR signal as
14
15 442 other authors have noted (e.g. see [42]). This radar absorption would be exacerbated
16
17 443 by the pig-chest cavity having collapsed during decomposition stages as noted in [47],
18
19 444 which is a probable explanation for the two GPR hyperbolae still present in 225 and
20
21 445 450 MHz dominant frequency data over the target location (Fig. 6A/B). 225 MHz
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23 446 dominant frequency antennae was shown in this study to be preferable to the other
24
25 447 frequencies trialled (110, 450 and 900 MHz frequencies) in the 2D profiles due to a
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27 448 detectable anomaly, target resolution and fewer non-target hyperbolae present in the
28
29 449 relative higher frequency data; note also forensic 225 MHz frequency radar surveys
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31 450 also took less time in the field to acquire when compared to their higher frequency
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33 451 versions. This could be an important factor for a forensic search team to consider if
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35 452 the proposed area is significant in size or if manpower and/or budget are limited. This
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37 453 agrees with others (e.g. [42]) who also suggested that 2D GPR profiles should be
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39 454 collected in both orientations over a survey site if possible to have the best chance of
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41 455 detection.
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49 457 *C) When was the optimal time (both up to six years post-burial and seasonally) to*
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51 458 *undertake a forensic GPR or electrical resistivity geophysical search survey?* Clearly
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53 459 from the results shown in this study and others (e.g. [42]) the burial style is key, it
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55 460 would be difficult to detect a naked burial after the first 18 months of burial using the
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3 461 resistivity and GPR survey methods detailed here and in [47]. However, note that
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5 462 other studies have shown favourable GPR survey results over much older burials in
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7 463 different ground conditions (eg. ([3,34,54,55])). Whilst there is a general reduction in
8
9 464 hyperbola quality in both burial styles, with the naked cadaver being much more
10
11 465 difficult to detect, there is a seasonal effect, with autumn and winter surveys,
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13 466 especially in years four to six post burial, generally better at resolving the targets.
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15
16 467 This has also been observed by authors geophysically monitoring simulated
17
18 468 clandestine burials on shorter time scales (e.g. [42]).
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21 469
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23 470 The resistivity surveys also showed a similar pattern, especially the fixed-offset
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25 471 electrical resistivity surveys which, when following [46] methodology to numerically
26
27 472 measure resistivity anomaly relative areas over time, consistently showed winter
28
29 473 surveys were optimal (Table 1). Each autumn to winter the anomalies over both the
30
31 474 naked and wrapped cadavers increased in area and reduced in normalised standard
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33 475 deviation (SD) values whereas they were comparably smaller and had larger SD
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35 476 values in the summer months (Fig. 8). The naked cadaver's anomaly and the
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37 477 normalised SD of the datasets got progressively smaller over time, but the wrapped
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39 478 cadaver's relatively high resistance anomaly increased in size over the six year study
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41 479 period (Fig. 8). Temporally varying resistivity anomalies over fixed archaeological
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43 480 targets have also been reported by [56] who undertook time-lapse resistivity surveys
44
45 481 over UK Roman fortification defence ditches. This study therefore shows the cyclical
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47 482 nature of low winter/spring SD values and high summer/autumn SD values repeating
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49 483 each year that was most probably due to the soil having reduced moisture content
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51 484 during the warmer and dryer periods but, importantly, in a non-uniform manner for
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53 485 this study site. Thus the 'noise' present within the geophysical data significantly
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3 486 increased during these seasonal periods and effectively 'masked' the target(s). See
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5 487 ([52] and [57] for detailed analysis of site soil moisture for the first two years of
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7 488 burial.
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11 **FIG. 8. - position**
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16 492 *D) When should a forensic geophysical survey be undertaken in a six year search*
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18 493 *scenario?* From this and other studies (e.g. 38-42,44]), clearly the burial style is still
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20 494 key; although the wrapped grave was initially harder to detect with electrical
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22 495 resistivity surveys (as shown in [47]), in this paper it is relatively easier to detect after
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24 496 four to six years of burial (Fig. 7). The wrapping also makes the target easier to find
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26 497 with GPR as the wrapping makes a good reflective target (Table 1). So although
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28 498 wrapping may help to conceal a body in some ways (for example, it may trap scent
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30 499 and prevent decompositional fluids leaching into the soil), it may also make a body
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32 500 easier to find geophysically. If the burial style is not known, then it is suggested that
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34 501 both electrical and GPR surveys be undertaken to have the best chance of successful
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36 502 detection. Note a naked cadaver would be progressively more difficult to find after 18
37
38 503 months of burial as shown in this (Table 1) and other studies (see [38-42,44]), and
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40 504 therefore other complementary methods should be trialled (e.g. search cadaver dogs).
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48 506 This study also reinforces other research (see e.g. 38-42,44,56]) the importance of
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50 507 when a forensic geophysical survey should be conducted within the year, seasonality
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52 508 has shown to be surprisingly important, and, if operational time permits, then
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54 509 geophysical surveys should be undertaken in winter to have the best chance of target
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56 510 detection success. If a past forensic geophysical search was unsuccessful, perhaps the
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3 511 results should be reviewed in terms of seasonality and perhaps re-surveyed if the
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5 512 original survey season was unfavourable. If there is a time-restricted element to the
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7 513 forensic search, then the season of surveying should be undertaken and an appropriate
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10 514 alternative search method should be chosen if necessary.

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14 516 From this long-term simulated grave monitoring study and comparing results from
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16 517 [24,27],29,38-42, 44,57-60], we still recommend that forensic geophysical surveys
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18 518 should be undertaken prior to other, more invasive search methods (e.g. metal
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21 519 detectors, soil/methane probes and cadaver dog probes). Any resulting soil
22
23 520 disturbances from these surveys would lead to more false positives for the resulting
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25 521 geophysical surveys, as found during the [29] forensic resistivity search. Once
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27 522 anomalous geophysical areas within the survey area are identified, these should be
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29 523 prioritised and then subjected to more detailed scientific investigations, which
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31
32 524 includes geophysical surveys (e.g. 2D ERI profiles, higher frequency 2D/3D GPR
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34 525 surveys), cadaver dogs, invasive probing, etc. See [11] for other geoscience search
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36 526 methods and suggested phased investigative approaches.

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3 529 **Conclusions and further work**
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5 530

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7 531 Geophysical long-term monitoring survey results over the simulated clandestine
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9 532 burials shown in this study and by others in different soil types should be used both to
10
11 533 assist forensic search investigators to use the appropriate search technique and
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13 534 equipment configuration, and indeed as a reference to allow comparison of data
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15 535 collected by forensic search investigators looking for similar clandestine burials of
16
17 536 murder victims.
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22
23 538 *A buried 'naked' victim* within a clandestine burial, if shallowly buried, should be
24
25 539 able to be located within the first 4 years of burial using twin electrode electrical
26
27 540 resistivity surveys. If the burial depth is unknown, the use of wider electrode
28
29 541 separations in addition to the most frequently used 0.5 m spacing is recommended.
30
31 542 Resistivity surveys are also recommended to be undertaken in clay-rich soils over
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33 543 GPR surveys due to the likelihood of highly conductive 'leachate' being retained in
34
35 544 the surrounding soil and GPR experiencing poor penetration depths in these soil types.
36
37 545 However after this time period a naked victim would become progressively more
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39 546 difficult to locate using electrical methods, with the majority of the decompositional
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41 547 fluids migrating away from the target, depending upon the soil type. However, ERI
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43 548 2D profiles could potentially still locate naked victims up to five years of burial if
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45 549 sited over it. 110 – 225 MHz dominant frequency GPR surveys could detect targets
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47 550 well up to 18 months of burial, then 225 MHz frequency poorly in winter months up
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49 551 to five years of burial due to decomposition, although skeletal material may still be
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51 552 imaged depending on target(s) depth and specific site conditions. If time and
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53 553 manpower availability permits then winter surveys should be undertaken.
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5 555 *A buried 'wrapped' or clothed victim* within a clandestine burial, if shallowly buried,6
7 556 should be able to be located using both fixed-offset electrical resistivity and ERI 2D8
9 557 Profile surveys throughout the six year monitoring period; in fact in this study it10
11 558 became progressively easier to detect the wrapped cadaver as the burial period12
13 559 extended. Medium (225-450 MHz) dominant frequency GPR antennae were deemed14
15 560 optimal frequency for detection due to good target resolution as other authors have16
17 561 evidenced (e.g. [41-42]); less non-target anomalies and data acquisition speed,18
19 562 although 110 MHz and 450 MHz frequency antennae data also resolved the wrapped20
21 563 grave throughout the study period, most probably due to the 'wrapping' producing a22
23 564 good reflective contrast. If time and manpower availability permits then winter24
25 565 surveys should be undertaken.26
27 56628
29 567 This study site will be continued to be monitored annually to discover *at what time*30
31 568 period after burial will geophysical surveys not be able to determine the location of a32
33 569 clandestine burial. Organic, inorganic and other analytical measurements are34
35 570 currently being undertaken to examine what may be causing the variability in grave36
37 571 'soilwater' conductivity after burial with preliminary results looking promising [61].38
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41 573 Further analysis of the geophysical data will also be undertaken; both to determine if42
43 574 there are diagnostic GPR signal spectra for clandestine burials versus background44
45 575 signals and to determine if both GPR and resistivity datasets can be simultaneously46
47 576 inverted numerically to quantify anomaly location(s), sizes and to quantitatively48
49 577 combine these two geophysical search techniques.50
51 578

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3 579 This experimental methodology should be repeated on similar time scale in other,
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5 580 contrasting soil types, in order to determine if soil type is a major factor in the ability
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7 581 of forensic geophysical surveys to successfully locate a clandestine burial. On a
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10 582 longer time scale, it is planned that the experiment will be repeated using human
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12 583 cadavers rather than pig analogues, as this may be an important variable to consider.
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587

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595

596 **References:**

597

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

601

602 2. Larson DO, Vass A A, Wise M. Advanced scientific methods and procedures in the
603 forensic investigation of clandestine graves. J Contemp Crim Justice 27 2011;27:149–
604 82.

605

606 3. Davenport GC. Remote sensing applications in forensic investigations. Hist Arch
607 2001;35:87–100.

608

609 4. Killam EW. The detection of human remains. Springfield: Charles C Thomas,
610 2004.

611

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

614

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

617

- 1
2
3 618 7. Lasseter A, Jacobi KP, Farley R, Hensel L. Cadaver dog and handler team
4
5 619 capabilities in the recovery of buried human remains in the Southeastern United
6
7 620 States. *J For Sci* 2003;48:1–5.
8
9 621
10
11 622 8. Pye K, Croft, DJ. *Forensic Geoscience: Principles, Techniques and Applications*.
12
13 623 London: Geol Soc London Spec Pub 232, 2004.
14
15 624
16
17 625 9. Ruffell A, McKinley J. *Forensic geoscience: applications of geology,*
18
19 626 *geomorphology and geophysics to criminal investigations*. *Earth Sci Rev*
20
21 627 2005;69:235–47.
22
23 628
24
25 629 10. Ruffell A, McKinley J. *Geoforensics*. Chichester: Wiley, 2008.
26
27 630
28
29 631 11. Pringle JK, Ruffell A, Jervis JR, Donnelly L, McKinley J, Hansen J, Morgan R,
30
31 632 Pirrie D, Harrison M. The use of geoscience methods for terrestrial forensic searches.
32
33 633 *Earth Sci Rev* 2012a;114:108-23.
34
35 634
36
37 635 12. Davenport GC, Griffin TJ, Lindemann JW, Heimmer D. Geoscientists and law
38
39 636 enforcement officers work together in Colorado. *Geotimes* 1990;35:13–5.
40
41 637
42
43 638 13. Brilis GM, Gerlach CL, van Waasbergen RJ. Remote sensing tools assist in
44
45 639 environmental forensics. Part I. Digital tools—traditional methods. *Env For*
46
47 640 2000a;1:63–7.
48
49 641
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 642 14. Brilis GM, van Waasbergen RJ, Stokely PM, Gerlach CL. Remote sensing tools
4
5 643 assist in environmental forensics. Part II. Digital tools. *Env For* 2000b;1:1–7.
6
7 644
8
9 645 15. Hunter J, Cox M. *Forensic archaeology: advances in theory and practice*.
10
11 646 Abingdon: Routledge, 2005.
12
13 647
14
15 648 16. Dickinson DJ. The aerial use of an infrared camera in a police search for the body
16
17 649 of a missing person in New Zealand. *J For Sci Soc* 1976;16:205–11.
18
19 650
20
21 651 17. Ruffell A, McKinley J. Forensic geomorphology. *Geomorph* 2014;206:14-22.
22
23 652
24
25 653 18. Owsley DW. Techniques for locating burials, with emphasis on the probe. *J For*
26
27 654 *Sci* 1995;40;735–40.
28
29 655
30
31 656 19. Ruffell A. Burial location using cheap and reliable quantitative probe
32
33 657 measurements. *For Sci Int* 2005a;151:207-11.
34
35 658
36
37 659 20. Hunter J, Simpson B, Sturdy Colls C, *Forensic approaches to buried remains*
38
39 660 (essential forensic science). Chichester: Wiley, 2013.
40
41 661
42
43 662 21. Reynolds JM. *An introduction to applied and environmental geophysics*, 2nd ed,
44
45 663 Chichester: Wiley-Blackwell, 2011.
46
47 664
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 665 22. Mellet JS. Location of human remains with ground penetrating radar. In:
4
5 666 Hanninen, P, Autio S, editors. Proc Fourth Int Conf on GPR, 1992 Jun 8-13;
6
7 667 Rovaniemi, Geological Surv Finland Spec Paper 16;359–65.
8
9 668
10
11 669 23. Calkin SF, Allen RP, Harriman MP. Buried in the basement – geophysics role in a
12
13 670 forensic investigation. Proc of symp Appl Geophys Eng environ problems; 1995,
14
15 671 Denver: Env Eng Geophys Soc;397–403.
16
17 672
18
19 673 24. Nobes DC. The search for “Yvonne”: a case example of the delineation of a
20
21 674 grave using near-surface geophysical methods. J For Sci 2000;45:715–21.
22
23 675
24
25 676 25. Scott J, Hunter JR. Environmental influences on resistivity mapping for the
26
27 677 location of clandestine graves. In: Pye K, Croft DJ, editors. Forensic Geoscience:
28
29 678 Principles, Techniques and Applications. London: Geol Soc London Spec Pub
30
31 679 2004;232:33–8.
32
33 680
34
35 681 26. Cheetham P. Forensic geophysical survey. In: Hunter J, Cox M, editors. Forensic
36
37 682 Archaeology: Advances in Theory and Practice, Abingdon: Routledge, 2005;62–95.
38
39 683
40
41 684 27. Ruffell A. Searching for the IRA “disappeared”: Ground Penetrating radar
42
43 685 investigation of a churchyard burial site. J For Sci 2005;50:1430-5.
44
45 686
46
47 687 28. Schultz JJ. Using ground-penetrating radar to locate clandestine graves of
48
49 688 homicide victims: forming forensic archaeology partnerships with law enforcement.
50
51 689 Homicide Studies 2007;11:15-29.
52
53
54
55
56
57
58
59
60

- 1
2
3 690
4
5 691 29. Pringle JK, Jervis JR. Electrical resistivity survey to search for a recent
6
7 692 clandestine burial of a homicide victim, UK. For Sci Int 2010;202(1-3):e1-7.
8
9 693
10
11 694 30. Novo A, Lorenzo H, Ria F, Solla M. 3D GPR in forensics: finding a clandestine
12
13 695 grave in a mountainous environment. For Sci Int 2011;204:134-8.
14
15 696
16
17 697 31. Schultz JJ. The application of GPR for forensic grave detection. In: Dirkmaat DC,
18
19 698 editors. A companion to forensic anthropology, Hoboken, NJ: Blackwell, 2012, p.85-
20
21 699 100.
22
23 700
24
25 701 32. Ruffell A, Pringle JK, Forbes S. Search protocols for hidden forensic objects
26
27 702 beneath floors and within walls. For Sci Int 2014;237:137-45.
28
29 703
30
31 704 33. France DL, Griffin TJ, Swanburg JG, Lindemann JW, Davenport GC, Trammell
32
33 705 V. et al. A multidisciplinary approach to the detection of clandestine graves. J For Sci
34
35 706 1992;37:1445–58.
36
37 707
38
39 708 34. Strongman KB. Forensic applications of ground penetrating radar. In: Pilon J,
40
41 709 editor. Ground Penetrating Radar, Ottawa: Geological Survey of Canada Paper 90-4,
42
43 710 1992;203–11.
44
45 711
46
47 712 35. Freeland RS, Miller ML, Yoder RE, Koppenjan SK. Forensic applications of
48
49 713 FMCW and pulse radar. J Env Eng Geophys 2003;8:97–103.
50
51 714
52
53
54
55
56
57
58
59
60

- 1
2
3 715 36. Pringle JK, Holland C, Szkornik K, Harrison M. Establishing forensic search
4
5 716 methodologies and geophysical surveying for the detection of clandestine graves in
6
7 717 coastal beach environments. *For Sci Int* 2012;219:e29-e36.
8
9 718
10
11 719 37. Pringle JK, Wisniewski K, Giubertoni M, Cassidy NJ, Hansen JD, Linford NJ,
12
13 720 Daniels RM. The use of magnetic susceptibility as a forensic search tool. *For Sci Int*
14
15 721 2015a;246:31-42.
16
17 722
18
19
20
21 723 38. Schultz JJ, Collins ME, Falsetti AB. Sequential monitoring of burials containing
22
23 724 large pig cadavers using ground-penetrating radar. *J For Sci* 2006;51:607-16.
24
25 725
26
27 726 39. Schultz JJ. Sequential monitoring of burials containing small pig cadavers using
28
29 727 ground-penetrating radar. *J For Sci* 2008;53:279-87.
30
31 728
32
33
34 729 40. Pringle JK, Jervis J, Cassella JP, Cassidy NJ. Time-lapse geophysical
35
36 730 investigations over a simulated urban clandestine grave. *J For Sci* 2008;53:1405-17.
37
38 731
39
40
41 732 41. Schultz JJ, Martin MM. Controlled GPR grave research: Comparison of reflection
42
43 733 profiles between 500 and 250 MHz antennae. *For Sci Int* 2011;209:64-9.
44
45 734
46
47 735 42. Schultz JJ, Martin MM. Monitoring controlled graves representing common burial
48
49 736 scenarios with ground penetrating radar. *J App Geophys* 2012;83:74-89.
50
51 737
52
53
54 738 43. Schotmans EMJ, Fletcher JN, Denton J, Janaway RC, Wilson AS. Long-term
55
56 739 effects of hydrated lime and quicklime on the decay of human remains using pig
57
58
59
60

- 1
2
3 740 cadavers as human body analogues: Field experiments. For Sci Int 2014a;238:141.e1-
4
5 741 e13.
6
7 742
8
9 743 44. Molina CM, Pringle JK, Saumett M, Hernandez O. Preliminary results of
10
11 744 sequential monitoring of simulated clandestine graves in Colombia, South America,
12
13 745 using ground penetrating radar and botany. For Sci Int 2015;248:61-70.
14
15 746
16
17 747 45. Pringle JK, Cassella JP, Jervis JR, Williams A, Cross P, Cassidy NJ. Soilwater
18
19 748 conductivity analysis to date and locate clandestine graves of homicide victims. J For
20
21 749 Sci in press.
22
23 750
24
25 751 46. Jervis JR, Pringle JK. A study of the affect of seasonal climatic factors on the
26
27 752 electrical resistivity response of three experimental graves. J App Geophys
28
29 753 2014;108:53-60.
30
31 754
32
33 755 47. Pringle JK, Jervis JR, Hansen JD, Cassidy NJ, Jones GM, Cassella JP.
34
35 756 Geophysical monitoring of simulated clandestine graves using electrical and Ground
36
37 757 Penetrating Radar methods: 0-3 years. J For Sci 2012b;57:1467-86.
38
39 758
40
41 759 48. Manhein MH. Decomposition rates of deliberate burials: a case study of
42
43 760 preservation. In: Haglund WD, Sorg MH, editors. Forensic taphonomy: the post-
44
45 761 mortem fate of human remains, Boca Raton, FL: CRC, 1996;469–81.
46
47 762
48
49 763 49. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-
50
51 764 Geiger climate classification. Hydro Earth Sys Sci 2007;11:1633–44.
52
53
54
55
56
57
58
59
60

1
2
3 7654
5 766 50. Vass AA, Bass WM, Wolt JD, Foss JE, Ammons JT. Time since death6
7 767 determinations of human cadavers using soil solution. *J For Sci* 1992;37:1236–53.8
9 76810
11 769 51. Carter DO, Tibbett M. Cadaver decomposition and soil: processes. In: Tibbett M,12
13 770 Carter DO, editors. *Soil Analysis in Forensic Taphonomy: Chemical and Biological*14
15 771 *Effects of Buried Human Remains*. Boca Raton: CRC Press, 2009;29–52.16
17 77218
19 773 52. Jervis JR, Pringle JK, Tuckwell GT. Time-lapse resistivity surveys over simulated20
21 774 clandestine burials. *For Sci Int* 2009;192:7-13.22
23 77524
25 776 53. Rodriguez WC. Decomposition of buried and submerged bodies. In: Haglund26
27 777 WD, Sorg MH, editors. *Forensic Taphonomy: The Postmortem Fate of Human*28
29 778 *Remains*. Boca Raton: CRC Press, 1997;459–68.30
31 77932
33 780 54. Hansen JD, Pringle JK, Goodwin J. GPR and bulk ground resistivity surveys in34
35 781 graveyards: locating unmarked burials in contrasting soil types. *For Sci Int*36
37 782 2014;237:e14-e29.38
39 78340
41 784 55. Bevan BW. The search for graves. *Geophysics* 1991;56:1310–9.42
43 78544
45 786 56. Clark AJ. *Seeing beneath the soil: prospecting methods in archaeology*, 2nd rev.46
47 787 ed. New York: Routledge, 1996.48
49 78850
51
52
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55
56
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2
3 789 57. Jervis JR. The detection of clandestine graves using electrical resistivity surveys:
4
5 790 results from controlled experiments and a case study (PhD dissertation). Keele: Keele
6
7 791 University, 2011.

8
9
10 792

11 793 58. Ellwood BB, Owsley DW, Ellwood SH, Mercado-Allinger PA. Search for the
12
13 794 grave of the hanged Texas gunfighter, William Preston Longley. *Hist Arch*
14
15 795 1994;28:94-112.

16
17
18 796

19
20 797 59. Ruffell A, McCabe A, Donnelly C, Sloan B. Location and assessment of an
21
22 798 historic (150-160 years old) mass grave using geographic and ground penetrating
23
24 799 radar investigation, NW Ireland. *J For Sci* 2009;54:382-94.

25
26
27 800

28
29 801 60. Powell K. Detecting human remains using near-surface geophysical instruments.
30
31 802 *Expl Geophys* 2004;35:88–92.

32
33
34 803

35
36 804 61. Blom G, Davidson A, Pringle J, Williams A, Lamont A, Cassella JP. Chemical
37
38 805 markers for the detection of clandestine graves – development of a complimentary
39
40 806 technique for forensic geophysics? Recent Work in Arch Geophys and For Geosci:
41
42 807 Future Horizons Conf, Geol Soc London, 2-3 December, 2014.

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3 810 **FIGURE CAPTIONS:**
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7 812 **FIG. 1.** (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI
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9 813 2D profile lines, lysimeter positions and UK location map all shown (inset). (B)
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11 814 Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and
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13 815 (F) soil fluid measurement photographs respectively. Modified from [47].
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18 817 **FIG. 2.** Summary of monthly study site statistics of total rainfall (bars) and average
19
20 818 temperature (line) data at 0.3 m bgl (below ground level), measured over the four to
21
22 819 six year study period. Dashed average temperature line is for zero to three years
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24 820 survey period [47] shown for comparison.
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29 822 **FIG. 3.** (A) Measured pig leachate (diamonds) and background (triangles) soil-water
30
31 823 fluid conductivity values over the 6-year survey period; 4-6 years to the right of the
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33 824 vertical dotted line. (B) Measured soil-water conductivity versus accumulated degree
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35 825 day (ADD) plot produced from (A) by summing average daily 0.3 m bgl after burial
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37 826 temperatures (see text). Best-fit linear correlation formulae and confidence (R²)
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39 827 values are also shown. Modified from [47].
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45 829 **FIG. 4.** Fixed-offset processed electrical resistivity datasets for the four to six year
46
47 830 study period (year and season shown). Red, green and blue rectangles indicate
48
49 831 positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).
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54 833 **FIG. 5.** Individually inverted 2D Electrical Resistivity Imaging (ERI) Wenner array
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56 834 (0.5 m spaced electrode) profiles for the four to six year study period (year and season
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3 835 shown); model inversion errors (RMS) for the fifth iterations are indicated. Positions
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5 836 of naked pig, empty and wrapped pig graves are also shown (dashed lines). See Fig.
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7 837 1A (ERI/ERI') for location.
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11 839 **FIG. 6(A).** Key sequential processed 110, 225, 450 and 900 MHz dominant
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14 840 frequency GPR profiles for 39 – 54 post-burial months (year and season shown) that
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16 841 bisect the naked and wrapped pig graves respectively (Fig. 1A for location).
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21 843 **FIG. 6(B).** Key sequential processed 110, 225, 450 and 900 MHz dominant
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23 844 frequency GPR profiles for 57 – 72 post-burial months (year and season shown) that
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25 845 bisect the naked and wrapped pig graves respectively (Fig. 1A for location).
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28 846

29 847 **FIG. 7.** Summary qualitative analysis plot of resistivity data over the complete six
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31 848 year survey period with this paper 4-6 year survey period to the right of the vertical
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33 849 dashed lines (see key and text). Modified from [47].
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38 851 **FIG. 8.** Summary quantitative analysis plots of fixed-offset resistivity data collected
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40 852 over the complete six year survey period with this paper 4-6 year survey period to the
41
42 853 right of the vertical dashed line. (A) Standard deviations (SD) for each survey, note
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44 854 SD values are highest in late summer; residual volume analysis of (B) naked pig
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46 855 cadaver and (C) wrapped pig cadaver (see text). Modified from [46].
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858 **TABLE CAPTION:**

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

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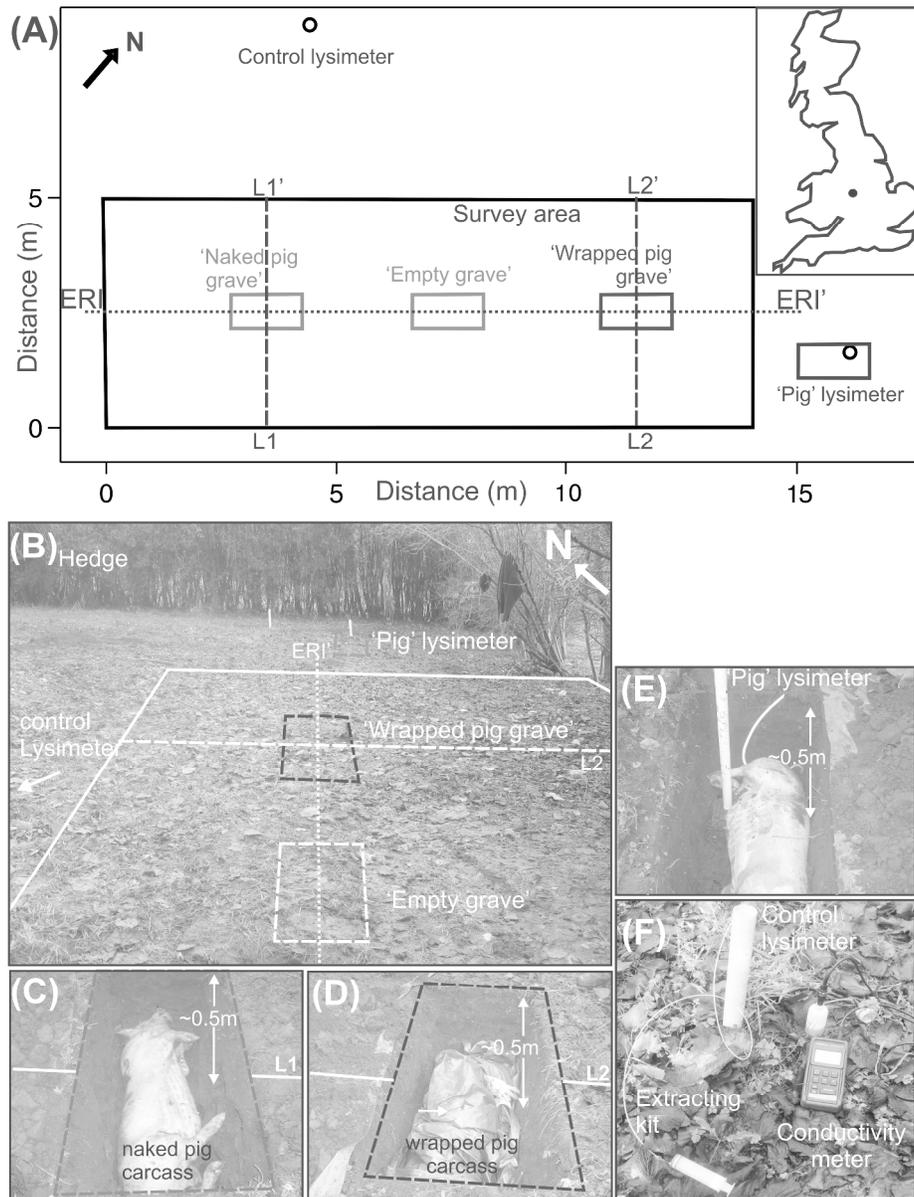


FIG. 1. (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI 2D profile lines, lysimeter positions and UK location map all shown (inset). (B) Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and (F) soil fluid measurement photographs respectively. Modified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

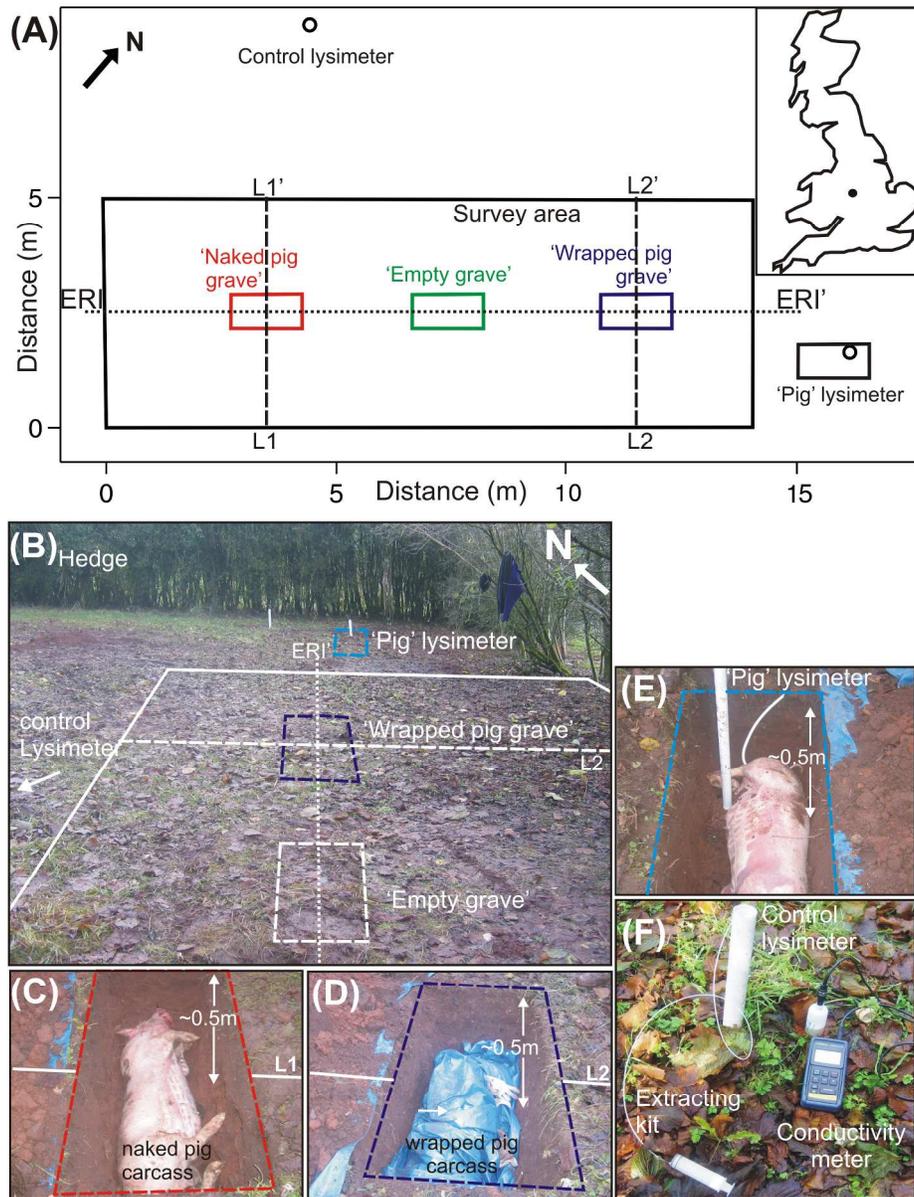


FIG. 1. (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI 2D profile lines, lysimeter positions and UK location map all shown (inset). (B) Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and (F) soil fluid measurement photographs respectively. Modified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

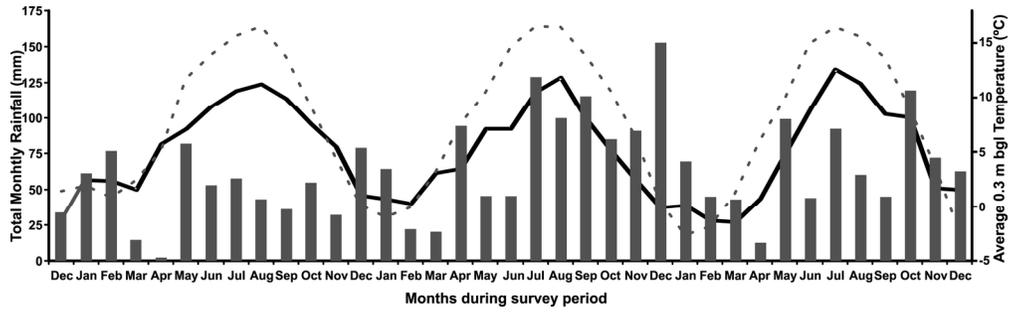
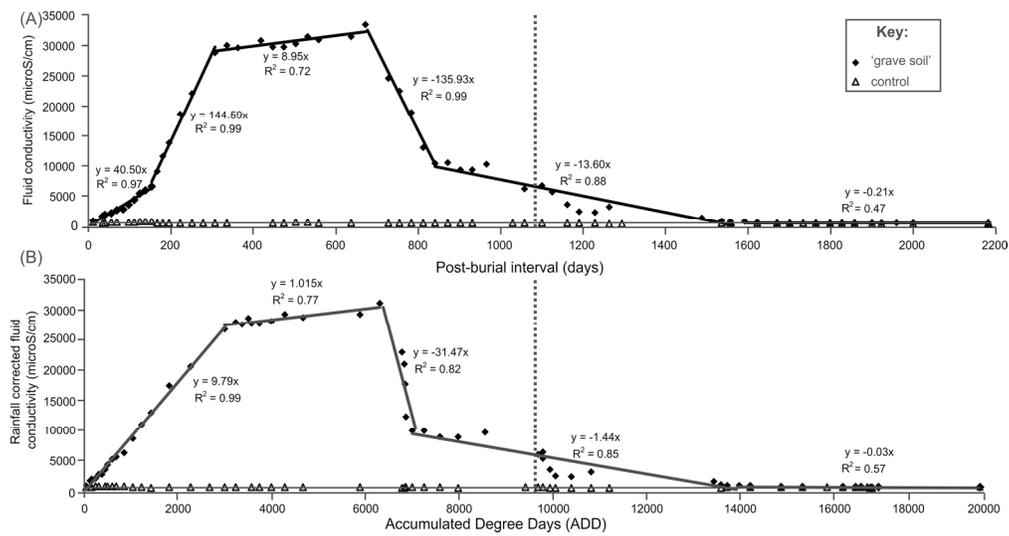


FIG. 2. Summary of monthly study site statistics of total rainfall (bars) and average temperature (line) data at 0.3 m bgl (below ground level), measured over the four to six year study period. Dashed average temperature line is for zero to three years survey period (40) shown for comparison.
86x25mm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



173x90mm (300 x 300 DPI)

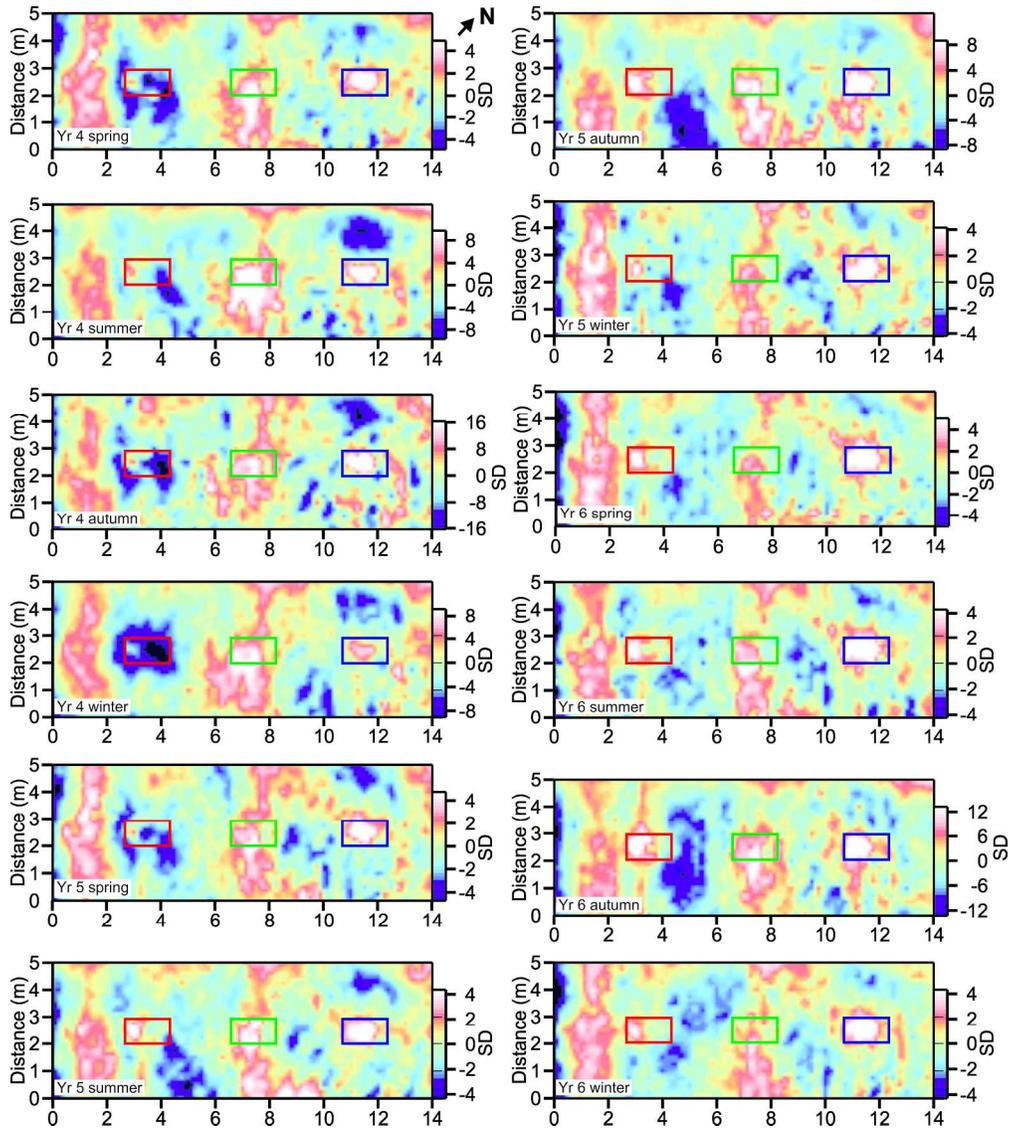


FIG. 4. Fixed-offset processed electrical resistivity datasets for the four to six year study period (year and season shown). Red, green and blue rectangles indicate positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).
209x235mm (300 x 300 DPI)

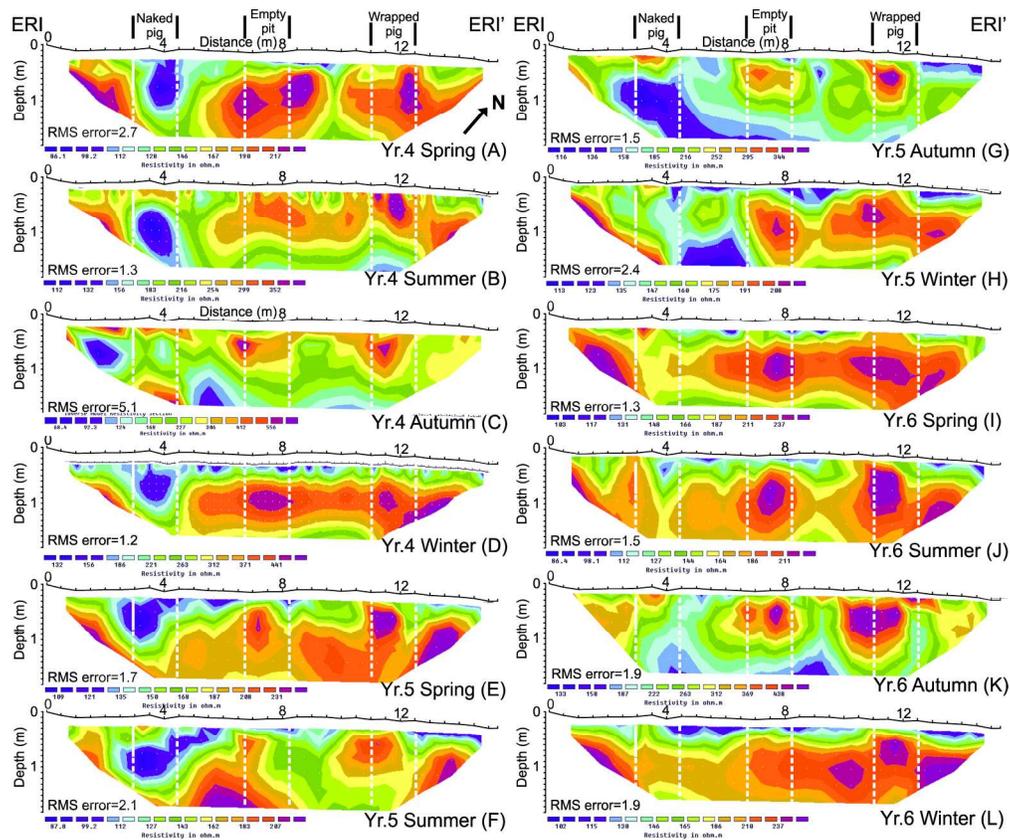


FIG. 5. Individually inverted 2D Electrical Resistivity Imaging (ERI) Wenner array (0.5 m spaced electrode) profiles for the four to six year study period (year and season shown); model inversion errors (RMS) for the fifth iterations are indicated. Positions of naked pig, empty and wrapped pig graves are also shown (dashed lines). See Fig. 1A (ERI/ERI') for location.

214x179mm (300 x 300 DPI)

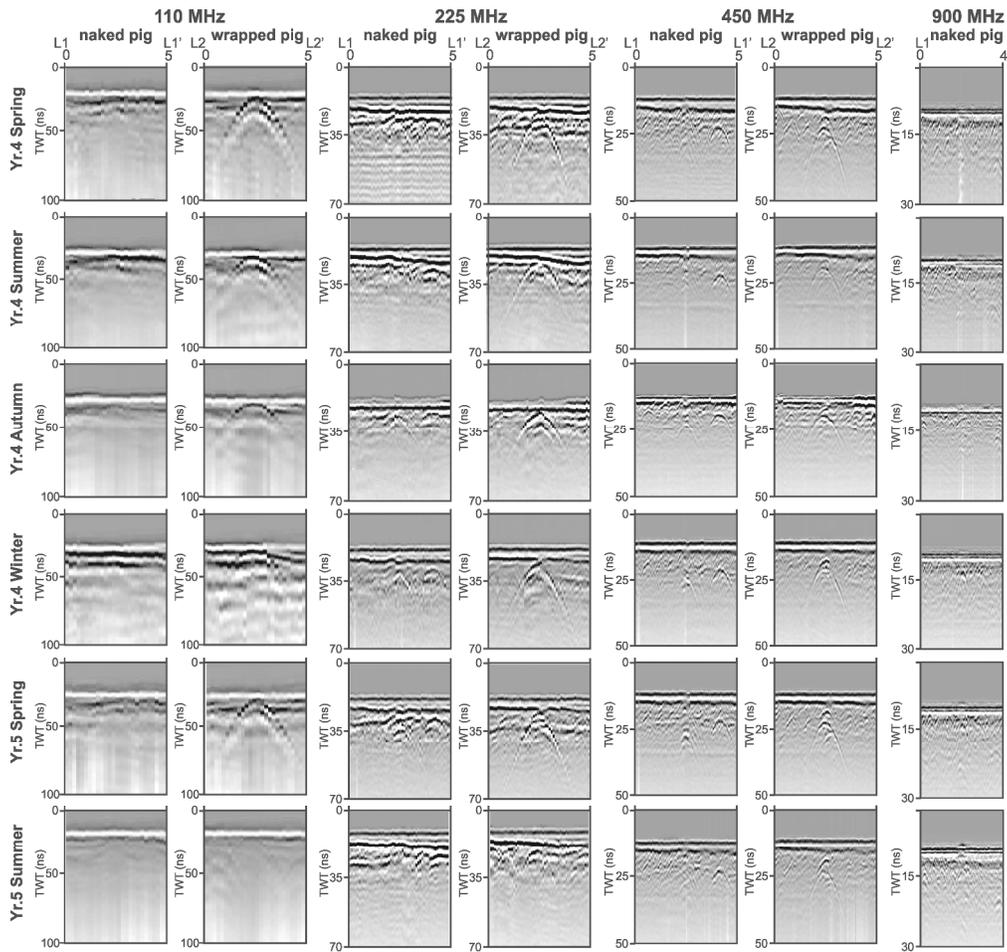


FIG. 6(A). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 39 – 54 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).
313x295mm (300 x 300 DPI)



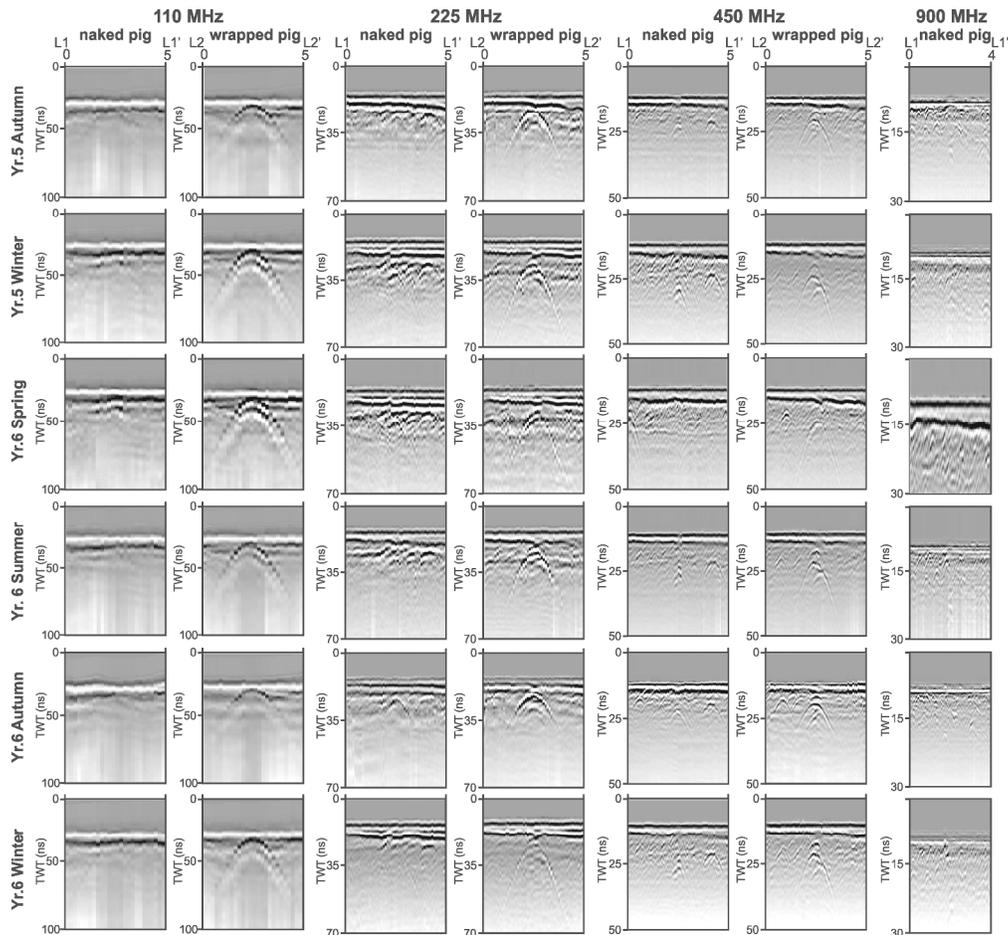


FIG. 6(B). Key sequential processed 110, 225, 450 and 900 MHz dominant frequency GPR profiles for 57 – 72 post-burial months (year and season shown) that bisect the naked and wrapped pig graves respectively (Fig. 1A for location).
317x295mm (300 x 300 DPI)



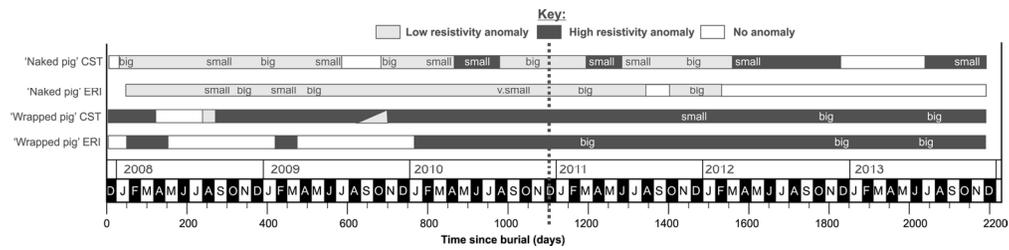


FIG. 7. Summary qualitative analysis plot of resistivity data over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed lines (see key and text). Modified from (40).
 76x18mm (600 x 600 DPI)

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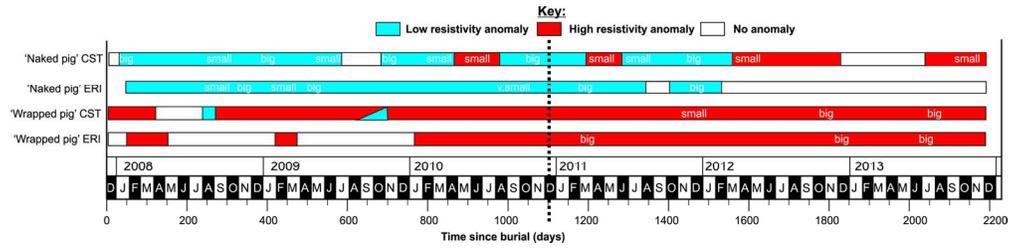


FIG. 7. Summary qualitative analysis plot of resistivity data over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed lines (see key and text). Modified from (40).
 76x18mm (600 x 600 DPI)

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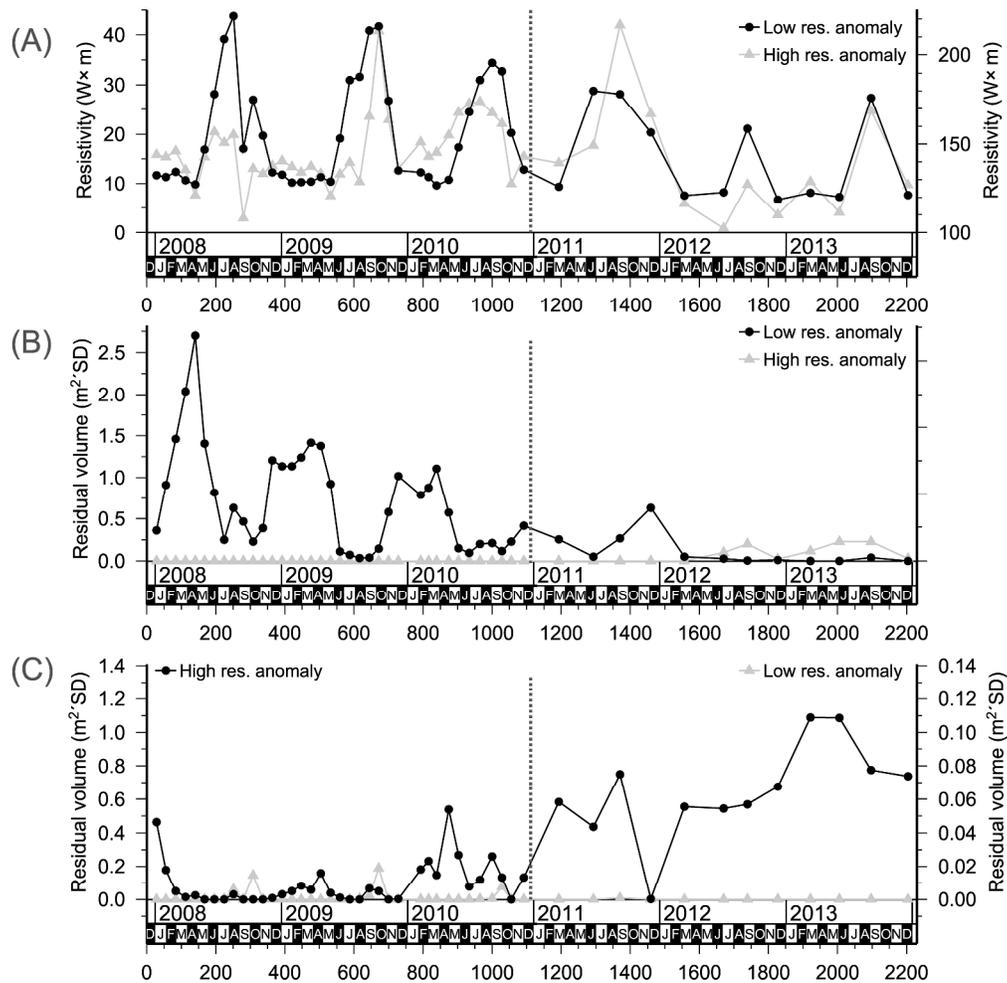


FIG. 8. Summary quantitative analysis plots of fixed-offset resistivity data collected over the complete six year survey period with this paper 4-6 year survey period to the right of the vertical dashed line. (A) Standard deviations (SD) for each survey, note SD values are highest in late summer; residual volume analysis of (B) naked pig cadaver and (C) wrapped pig cadaver (see text). Modified from (39). 176x171mm (600 x 600 DPI)

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

TABLE 1. Summary of geophysical surveys and their respective geophysical anomalies in this study (4-6 year results below

horizontal line). ⁺Burial date was 7th December 2007. *ADD date based on average daily site temperatures at 0.3 m bgl (see [47]).

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3 | **Long-term Geophysical monitoring of simulated clandestine graves using**
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5 2 **electrical and Ground Penetrating Radar methods: 4-6 years after burial**
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9 4 Jamie K. Pringle,¹ Ph.D.; John R. Jervis,^{1,2} Ph.D.; Daniel Roberts,¹ M.Sc.; Henry C.
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11 5 Dick,¹ B.Sc; Kris Wisniewski,¹ B.Sc; Nigel J. Cassidy,¹ Ph.D.; and John P. Cassella,³
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31 14 Sources of funding:
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36 16 A U.K. HEFCE SRIF2 equipment grant funded purchase of geophysical equipment.
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19 **ABSTRACT**

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21 This ongoing monitoring study provides forensic search teams with systematic

22 geophysical data over simulated clandestine graves for comparison to active cases.

23 Simulated ‘wrapped’, ‘naked’ and ‘control’ burials were created. Multiple

24 geophysical surveys were collected over six-years, here showing data from four to six

25 years after burial. Electrical resistivity (~~fixed-offset~~ twinned electrode and ERI), multi-

26 frequency GPR, grave and background soilwater were collected. Resistivity surveys

27 revealed the naked burial had low-resistivity anomalies up to year four but then

28 difficult to image, whereas the wrapped burial had consistent large high-resistivity

29 anomalies. GPR 110-900 MHz frequency surveys showed the wrapped burial could

30 be detected throughout, but the naked burial was either not detectable or poorly ~~to not~~

31 resolved. 225 MHz frequency GPR data were optimal. Soil water analyses showed

32 decreasing (year four-five) to background (year six) conductivity values. Results

33 suggest both resistivity and GPR surveying if burial style unknown, with winter to

34 spring surveys optimal and increasingly important as time increases.

35

36 **Keywords:** forensic science; forensic geophysics; clandestine grave; monitoring;37 electrical resistivity; ~~G~~ground ~~P~~penetrating ~~R~~adar; conductivity

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3 40 Forensic search methods vary widely, for example, in the UK a search strategist is
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5 41 usually involved in a case at an early stage to decide upon the highest probability of
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7 42 search success [1], whereas in other countries a search may not be methodical,
8
9 43 investigations may not be standardised and a variety of techniques are undertaken,
10
11 44 depending upon local experience [2]. Metal detector search teams [3-5] and specially
12
13 45 trained search dogs [5-7] are both commonly used during either initial investigations
14
15
16 46 or as part of a phased sequential programme.
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21 48 Forensic investigators have been increasingly using geoscientific methods to aid in
22
23 49 civil or criminal forensic investigations, predominantly to assist search teams or for
24
25 50 trace evidence purposes [8-11]. One key and high-profile 'target' for forensic search
26
27 51 teams to detect and locate is human remains buried within clandestine graves [1,5,12].
28
29 52 These searches generally start from large-scale remote sensing methods [13-14], aerial
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31 53 and ultraviolet photography [10,15], thermal imaging [16], to ground-based
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33 54 observations of vegetation changes [4], surface geomorphology changes [17], soil
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35 55 type [1] and depositional environment(s) [10], near-surface geophysics [11],
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37 56 diggability surveys [1] and probing of anomalous areas [18,19] before topsoil removal
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39 57 [4], and finally controlled excavation and recovery [5,15,20]. A typical search will
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42 58 only use a few of these techniques, depending on the circumstances of each case
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45 59 (Colin Hope, *pers. comm.*).
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50 61 Near-surface geophysical methods rely on there being a detectable physical contrast
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52 62 between the target and the background (or host) materials (see [21]). Near-surface
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54 63 geophysical surveys have been used to [try and](#) locate clandestine graves in a number
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56 64 of reported criminal search investigations [3,5,22-32]. Geophysical surveys collected
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3 65 | over simulated burials have been undertaken in order to collect control data (e.g. [33-
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5 66 | 37]. These studies have shown that the resulting geophysical responses could be well
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7 67 | predicted, although responses seem to vary both temporally after burial and between
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9 68 | different study sites. A few studies have also collected repeat (time-lapse)
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11 69 | geophysical surveys over controlled experiments (e.g. [26,38-44]), which have
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13 70 | documented temporal changes in geophysical responses over their study periods.
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15 71 | However, uncertainties still remain over what and how long temporal variations occur
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17 72 | in geophysical surveys after burial, with study survey sites needing to be fully
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19 73 | characterised (e.g. geologically and climatologically) to allow comparisons with other
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21 74 | studies or indeed for active forensic cases. Documenting temporal changes is
22
23 75 | important as geophysical responses from recent clandestine burials are known to vary
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25 76 | more than ~~for~~ archaeological graves. Potential reasons for this could be the temporal
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27 77 | changes in grave soil characteristics, decomposition products [45], climatic variations,
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29 78 | soil moisture content [46] and other site specific factors (see [11]).
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36 80 | This study continued the systematic assessment of the changing geophysical response
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38 81 | of simulated clandestine graves during four to six years after burial. Geophysical
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40 82 | survey results from zero to three years after burial were published in [47]. A
41
42 83 | clandestine grave was defined in this study as an unrecorded burial that has been
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44 84 | hand-excavated and dug <1 m depth below ground level (bgl). It should be noted that
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46 85 | geophysical results will vary depending upon the depth of burial and indeed on local
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48 86 | soil type as [11] reviews. The discovered graves published in [15,48] were usually
49
50 87 | rectangular in plan-view, mostly hurriedly hand dug using garden implements and
51
52 88 | usually just large enough to deposit the victim before being back-filled with excavated
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54 89 | soil and associated surface debris. [48] also detailed that almost half of the 87
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3 90 documented U.S. cases were either clothed or encased in material (plastic or fabric),
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5 91 so the authors decided to use two end member scenarios for this study; namely one
6
7 92 burial containing a *naked* cadaver and another containing a cadaver *wrapped* in a
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9
10 93 tarpaulin. It is, however, emphasised that these obviously do not represent all types of
11
12 94 potential style of burial [with \[42\] considering other scenarios.](#)

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16 96 There are many potential near-surface geophysical search techniques that could be
17
18 97 utilised to search for clandestine graves that the [47] monitoring paper summarises;
19
20 98 this ongoing study has concentrated on collecting electrical resistivity (fixed-offset
21
22
23 99 and Electrical Resistivity Imaging 2D profiles) and Ground Penetrating Radar (110 –
24
25 100 900 MHz frequency 2D profiles. [Resistivity surveys showed consistent low](#)
26
27 101 [anomalies, compared to background values, for a naked burial, in contrast with the](#)
28
29 102 [wrapped burial which had smaller and varied low/high anomalies and was thus harder](#)
30
31 103 [to locate \[47\]. Analyses of decompositional fluids showed highest conductivity](#)
32
33 104 [values, compared to background soilwater, was ~1 year to ~2 years after burial before](#)
34
35 105 [subsequently decreasing \[47\]. GPR surveys finally showed low frequency antennae](#)
36
37 106 [were consistently optimal for target detection \[47\].](#)

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43 108 The aims of this continued four to six year geophysical monitoring study of different
44
45 109 simulated burial style clandestine burials were to answer some basic questions posed
46
47 110 by forensic search teams. Appropriate site data (rainfall, temperature, soil and ‘grave’
48
49 111 water conductivities) were also continued to be simultaneously collected in order to
50
51 112 allow comparisons with other research studies and criminal search investigations.
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53 113 Basic forensic search questions which [will-were](#) continued to be addressed by this
54
55 114 study were:
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3 115 | A) firstly Could twin electrode (fixed-offset) and electrical resistivity imaging
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5 116 | surveys still successfully locate both simulated clandestine burials beyond three
6
7 117 | years after burial? And if so, how long were they geophysically detectable for?
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10 118 | B) Secondly Could single profile GPR surveys successfully locate both simulated
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12 119 | clandestine burials throughout the four to six year post-burial monitoring period?
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14 120 | If this was the case, which dominant frequency antenna was optimal to detect
15
16 121 | them?
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18 122 | C) Thirdly When was the optimal time (both up to six years post-burial and
19
20 123 | seasonally) to undertake a forensic GPR or electrical resistivity geophysical search
21
22 124 | survey?
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25 125 | A)D) Finally, When should a forensic geophysical survey be undertaken in a six year
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27 126 | search scenario?
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3 128 **Methodology**
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7 130 *Study site*
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11 132 The chosen controlled test site was located on Keele University campus, ~ 200 m
12
13 133 above sea level, close to the town of Newcastle-under-Lyme in Staffordshire, UK.

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15
16 134 The local climate is temperate, which is typical for the UK [49]. The study site was a
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18 135 grassed, small rectangular area (~25 m x ~25 m), surrounded by small deciduous trees
19
20 136 (Fig. 1). The geophysical survey area measured 5 m x 14 m and sloped by
21
22 137 approximately 3° from northwest to southeast. Within this area were the ‘naked pig’
23
24 138 grave, the empty grave and the ‘wrapped pig’ grave emplaced in sandy loam soil (Fig.
25
26 139 1). [47] provides other relevant background site information.
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31
32 141 The test site was located ~200 m from the Keele University weather observation
33
34 142 station, which continually measured daily rainfall and air and ground temperatures as
35
36 143 well as having soil temperature probes at 0.1 m, 0.3 m and 1.0 m below ground level.
37
38 144 Figure 2 shows a monthly summary of the total rainfall and average temperature data
39
40 145 over the monitoring period with temperature data for the zero to three year monitoring
41
42 146 study also shown for comparison. The local weather station data showed that total
43
44 147 monthly rainfall during the four to six year study period ranged from 2.6 mm to 152.2
45
46 148 mm, with an overall monthly average of 64.7 mm, the same as for the zero to three
47
48 149 year monitoring period [47]. Average monthly air temperatures ranged from -1.2 °C
49
50 150 to 12.8 °C, with an overall monthly average of 5.5 °C, 3.2 °C colder than for the zero
51
52 151 to three year monitoring period (Fig. 2). However, note at 0.3m bgl the average
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54 152 temperature was 10.2 °C for the three-four to six year monitoring period and 9.8 °C for
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3 153 | [the 0-3 year monitoring period \[47\]. Accumulated Degree Day \(ADD\) data \(see \[50\]](#)
4
5 154 | [for background\)](#) detailed in Table 1 quantified these temperature differences. All four
6
7 155 | ~~to six year monitoring period weather statistics were broadly similar when compared~~
8
9
10 156 | ~~to the 0-3 year monitoring period (see [47]), including below ground temperatures,~~
11
12 157 | ~~although surface temperatures were, on average, 2 °C relatively colder for the four to~~
13
14 158 | ~~six year monitoring period (Fig. 2).~~
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20 160 | **FIG. 1. -position**

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22 162 | **FIG. 2. -position**

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24 164 | *Simulated graves*

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26
27 166 | Five simulated graves were created at the site (Fig. 1A). Three of the graves were
28
29 167 | used for the repeat geophysical surveys, whilst ground water samples were collected
30
31 168 | at regular intervals from both the fourth grave and a separate control site situated ~10
32
33 169 | m upslope away from the graves (Fig. 1E-F), both of the soilwater sampling sites
34
35 170 | being outside the geophysical survey area (Fig. 1A). Of the three simulated graves
36
37 171 | geophysically surveyed, one contained a naked pig carcass, one contained a [wrapped](#)
38
39 172 | carcass [wrapped in woven PVC tarpaulin](#) and the third was an empty grave to act as a
40
41 173 | control (Fig. 1). Pig cadavers are commonly used in such monitoring experiments as
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43 174 | they comprise similar chemical compositions, size, tissue:body fat ratios and skin/hair
44
45 175 | type to humans [51,52]. The grave emplacement procedure was described in [47].
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57 177 | *Bulk ground water conductivity data collection*

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5 179 Ground water sample lysimeters were emplaced both within a grave containing a pig
6
7 180 carcass outside the geophysical survey area and a further lysimeter ~10 m from the
8
9 181 survey area to act as control (Fig. 1). The lysimeter emplacement and regular sample
10
11 182 collection (Table 1) and analysis procedures used in this study were the same as for
12
13 183 the initial three year monitoring period and are described in [47]. The only change
14
15 184 was the sample frequency with samples collected at approximately three-monthly
16
17 185 seasonal intervals during the four to six year monitoring period due to limited monthly
18
19 186 changes observed in the zero to three year monitoring period [47] and survey time
20
21 187 constraints (Table 1).
22
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27 **TABLE 1.**

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31
32 *Near surface geophysical data collection & processing*

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36 193 ~~Fixed offset Twin electrode (0.5 m fixed-offset)~~ resistivity surveys were conducted at
37
38 194 three monthly intervals over the geophysical survey area (Fig. 1A-B) during the four
39
40 195 to six year monitoring period (Table 1). Data ~~was collected~~ using the RM15
41
42 196 (Geoscan™ Research) resistivity meter on a 0.25 m by 0.25 m grid with remote
43
44 197 probes placed on the same position 17 m from the survey area for consistency. and
45
46 198 sSubsequent data processing methodology was the same as detailed in [47].
47
48
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51
52 200 A 2D Electrical Resistivity Imaging (ERI) survey line orientated SW-NE (Fig. 1A-B)
53
54 201 was surveyed at approximately three-monthly intervals (Table 1). 32 electrodes were
55
56 202 placed every 0.5 m along the 15.5 m long survey profile was 15.5 m long and that
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3 203 bisected all three graves (Fig. 1A). Geophysical survey collection using a Campus™
4
5 204 TIGRE system and subsequent inversion using Geotomo™ Res2Dinv v.355 software
6
7 205 used in this study were the same as for the initial three year monitoring period and are
8
9
10 206 described in [47].

11
12 207

13
14 208 Due to the variable results of horizontal time slices ~~that~~ GPR data generated in the
15
16 209 zero to three year monitoring survey period (see [47]), 2D GPR profiles were only
17
18 210 collected on two profiles within the survey area that bisected the two simulated graves
19
20 211 with pigs present (Fig. 1A) at approximately three-monthly intervals (Table 1). GPR
21
22 212 data collection using the PulseEKKO™ 1000 equipment utilised 110 MHz, 225 MHz,
23
24 213 450 MHz and 900 MHz dominant frequency antennae, with radar trace spacings being
25
26 214 0.2 m, 0.1 m, 0.05 m, and 0.025 m, respectively, using 32 “stacks” to increase the
27
28 215 signal-to-noise ratio and for all data sets for consistency purposes. ~~and s~~Subsequent
29
30 216 data processing were the same as for the initial three year monitoring period and are
31
32 217 described in [47], ~~except for migration and the horizontal time slices not being~~
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34 218 ~~generated.~~

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221 **Results**

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

230

231 *Bulk ground water conductivity*

232

233 Background soilwater conductivity measurements demonstrated that background
234 values were consistent over the three year monitoring period (averaging 355 ± 0.1
235 $\mu\text{S}/\text{cm}$ with 40 SD) that was comparable to the zero to three year monitoring period
236 (averaging $444 \pm 0.1 \mu\text{S}/\text{cm}$). However, the pig leachate conductivity continued to
237 reduce during year four (Fig. 3A), varying from $6,670 \pm 0.1 \mu\text{S}/\text{cm}$ (1,099 days after
238 burial) down to consistent and comparable background values of $356 \pm 0.1 \mu\text{S}/\text{cm}$
239 after 1,670 days of burial to the end of the monitoring period. Pig leachate
240 conductivity changes during the first three years of burial are reported in [47].

241 Leachate values in this study could be ~~grouped~~ divided into two clear linear groupings
242 ~~regressions~~ of conductivity against post-burial days; 840-1,670 burial days (which
243 included some data from the third year of monitoring) and 1,670 burial days to the
244 end of the survey period respectively (Fig. 3A). The first data grouping had a
245 decreasing regression line against burial days ~~had with~~ a reasonable fit ($R^2 = 0.88$),

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2
3 246 | ~~but with the correlation for the second data grouping having a flat regression line,~~
4
5 247 | ~~albeit with a relatively poor correlation ($R^2 = 0.47$) due to its flat nature, evidencing~~
6
7 248 | ~~that pig leachate conductivity was consistently at background soilwater values~~
8
9 249 | ~~line~~
10 | ~~was much lower ($R^2 = 0.48$), see(Fig. 3A).~~
11

250

251 **FIG. 3. - position**

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18 253 | Site temperature variation could be removed from raw conductivity values as
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20
21 254 | discussed in [47 Pringle et al. 2012 jfs] by weighting each day by its average daily
22
23 255 | temperature and then giving each day after burial an accumulated degree day (ADD)
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25 256 | following standard methods [50]. This study still had the advantage of having
26
27 257 | temperature probe measurement data available from the actual mid-cadaver depth
28
29 258 | (~0.3m bgl) from the nearby meteorological weather station, instead of using average
30
31 259 | air temperatures (Fig. 2). This ~~again~~ allowed the ~~generation-separation~~ of two ~~data~~
32
33 260 | ~~groupings with two~~ linear regression correlations to be generated of conductivity
34
35 261 | against ADD, with similar fits to those generated against post-burial days (R^2 values
36
37 262 | of 0.86 and 0.57 respectively), see Fig. 3B.
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263

264 | ~~Twin electrode Bulk ground (fixed-offset) resistivity~~

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47 266 | Bulk ground resistivity surveys acquired over the four to six year monitoring study
48
49 267 | period were again remarkably consistent, with average fixed-offset survey resistance
50
51 268 | values of 63.6 Ω (with 47.0 Ω minimum and 99.4 Ω maximum values respectively)
52
53 269 | (compared to an average of 67.1 Ω for zero to three years), ~~afteronce~~ de-spiking data
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55 270 | ~~processing had been undertaken~~ (only averaged 1.6 anomalous 'spike' per survey).
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3 271 The three monthly processed fixed-offset resistivity surveys are graphically shown in
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5 272 Figure 4 (see Fig. 1A for 'grave' locations) and summarised in Table 1.

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10 274 As found in the zero to three year monitoring datasets, the empty grave which acted as
11
12 275 control could not be geophysically detected throughout the survey period (green boxes
13
14 276 in Fig. 4). The naked pig grave (red boxes in Fig. 4) was anomalously temporally

15
16 277 variable throughout the four to six year monitoring period, mostly comprising a small
17
18 278 (<0.6 m² SD) amplitude mixed low/high anomaly, when compared to background

19
20
21 279 values (Fig. 4 and Table 1). It only comprised a large low anomaly with a low

22
23 280 resistivity (coloured blue) in the winter Year 4 dataset that was consistently observed

24
25 281 in the zero to three year monitoring datasets (see [40] and Table 1). In contrast, the

26
27 282 wrapped pig grave (blue boxes in Fig. 4) showed predominantly a large (>0.6 m² SD)

28
29 283 amplitude high resistivity anomaly (coloured red/white), when compared to

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31
32 284 background values, that was mostly Good to Excellent rating and appeared to have

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34 285 increased in size from the zero to three year monitoring dataset immediately after

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36 286 burial (see [47] and Table 1).

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40 288 **FIG. 4. – position**

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45 290 *Electrical resistivity imaging (ERI)*

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49 292 After de-spiking data, electrical resistivity imaging surveys acquired over the four

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51 293 to six year monitoring study period were also again consistent, with average ERI six

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53 294 'n' level survey resistivity values of 197.0 Ω.m with 106.0 Ω.m minimum and 318.9

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55 295 Ω.m maximum respectively (compared to an average of 161.8 Ω for zero to three

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3 296 | years), ~~once de-spiking data processing had been undertaken~~. A summary of the 2D
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5 297 | ERI profiles collected is graphically shown in Figure 5 (see Fig. 1A for profile
6
7 298 | location) and summarised in Table 1. An average inversion model error (RMS) of 2.1
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9 299 | (with 1.2 minimum and 5.1 maximum) after five iterations again indicated a very
10
11 300 | good model inversion fit to the collected resistivity values (compared to a RMS of
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13 301 | 2.82 for zero to three years),.
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16 302

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18 303 | The empty grave (marked in Fig. 5) again could be detected throughout the survey
19
20 304 | period, although, in contrast to the zero to three year monitoring period, it had
21
22 305 | consistently higher resistivity values, when compared to neighbouring regions (Fig.
23
24 306 | 5). The naked pig grave was again generally detectable as a consistent Good rated
25
26 307 | anomalous low, when compared to background values up to the end of year five,
27
28 308 | although thereafter it was difficult to resolve from neighbouring regions (Fig. 5 and
29
30 309 | Table 1). The wrapped pig grave was mostly surprisingly detectable as a large high
31
32 310 | Good rated resistivity anomaly, when compared to background values, although the
33
34 311 | anomaly ~~it~~ was relatively smaller in the summer and autumn of year's four and five
35
36 312 | (Fig. 5). In the zero to three year monitoring survey the high resistivity anomaly was
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38 313 | relatively smaller ~~was a relatively small high resistivity anomaly in the zero to three~~
39
40 314 | year monitoring survey period (see [47] and Table 1).
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48 316 | **FIG. 5. - position**
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50 317 |
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52 318 | *Ground Penetrating Radar (GPR)*
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3 320 The 2D GPR profiles acquired through~~out~~ the four to six year monitoring survey
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5 321 period are shown in Figure 6A and 6B (see Fig. 1A for profile locations) ~~and~~
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7 322 ~~summarised in Table 1~~. The 110 MHz dominant frequency 2D profiles showed the
8
9 323 wrapped pig grave could still be consistently and clearly identified by a strong *Good*
10
11 324 ~~to Excellent rated~~ hyperbola throughout the survey period (except for year 5 summer),
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13
14 325 although there was a continual reduction in reflection amplitudes. This was in
15
16 326 contrast to the naked pig grave which was ~~either barely to-not detectable or at best~~
17
18 327 ~~produced as a Poor rated~~ hyperbola throughout ~~theis~~ survey period (see Fig.6A and
19
20 328 6B ~~and Table 1~~). There were no clear hyperbolae other than those associated with the
21
22
23 329 target graves within these 2D profiles.
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25
26 330

27 331 The 225 MHz dominant frequency 2D profiles still showed the wrapped pig grave
28
29 332 could be clearly identified by an obvious *Good to Excellent rated* hyperbola
30
31 333 throughout the four to six year monitoring survey period, although there was also a
32
33 334 continual reduction in reflection amplitudes (see Fig.6A and 6B). The second,
34
35 335 slightly deeper reflector that was first resolved after 15 months of burial within the
36
37 336 wrapped pig grave (see [47]) was still present in this dataset. The naked pig grave
38
39 337 was ~~difficult-given a Poor to None rating of to-detect-as-a~~ hyperbola anomaly
40
41 338 throughout the four to six year monitoring survey period although it was *possible*
42
43 339 ~~tojust detectable~~ in the autumn and winter data ~~of year 4~~ (Fig. 6A/B). As per the zero
44
45 340 to three year monitoring survey results [47], there were other, smaller hyperbolae
46
47 341 present in the naked pig profiles that were not associated with the target. ~~This s-which~~
48
49 342 would have made it difficult to identify the target grave if the position was not known.
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51
52 343 ~~However, note they may have been detected if data were collected orthogonally to the~~
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3 344 | primary survey line orientation or indeed if time slices were generated (although the
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5 345 | zero to three year survey time slice data detailed in [47] was poor).
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10 347 The 450 MHz dominant frequency 2D profiles showed the wrapped pig grave could
11
12 348 | be identified by a Good to Excellent rated hyperbola throughout the four to six year
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14 349 | monitoring survey period, but this had a consistently low amplitude (see Fig.6A and
15
16 350 | 6B and Table 1). The second, slightly deeper hyperbola observed after 3 months of
17
18 351 | burial was still present during this survey period. The naked pig grave was rated as
19
20 352 | poorly-Poor to None rated detectable as a hyperbola throughout the four to six year
21
22 353 | monitoring period. There were again numerous other, smaller hyperbolae present in
23
24 354 | both profiles that were not associated with the target grave which would have made it
25
26 355 | difficult to identify the target grave if the position was not known. These may, again
27
28 356 | have been detected if data were collected orthogonally to the primary survey line
29
30 357 | orientation or indeed if time slices were generated (although the zero to three year
31
32 358 | survey time slice data detailed in [47] was again poor).
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36 359

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38 360 | The 900 MHz dominant frequency 2D profiles was rated Poor to None rated so was
39
40 361 | difficult to ~~could not~~ identify the naked pig grave throughout the four to six year
41
42 362 | monitoring period (see Fig.6A and 6B). There were numerous other, smaller
43
44 363 | hyperbolae present which would also have made it difficult to locate the target grave,
45
46 364 | although orthogonal surveys may have been successful.
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52 366 | **FIG. 6(A).**

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56 368 | **FIG. 6(B).**
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3 369 **Discussion**
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5 370

6
7 371 This study is the first published research to systematically detail resistivity, GPR and
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10 372 site monitoring data over a simulated clandestine grave test site over six years of
11
12 373 burial [summarised in Table 1](#). Importantly both naked and wrapped cadavers have
13
14 374 been emplaced and surveyed which provides the two main burial styles encountered
15
16 375 in discovered clandestine graves of murder victims. This has allowed questions by
17
18 376 forensic search teams listed in the introduction to be answered that has not been able
19
20
21 377 to be undertaken to date. These will be sequentially discussed and are deliberately
22
23 378 similar to those posed in the zero to three year monitoring paper [\[47\]](#).
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26
27 380 *Firstly, A) eCould [twin electrode \(fixed-offset\) and electrical resistivity imaging](#)*
28
29 381 *surveys [still successfully locate the 'naked' and 'wrapped' simulated clandestine](#)*
30
31 382 *burials beyond three years after burial? And if so, how long were they geophysically*
32
33 383 *detectable for?* From the results of this long-term study, the answer was, it still
34
35 384 depends on the burial style. The fixed-offset electrical resistivity surveys showed that
36
37 385 a naked cadaver(s) has a good chance of being located up to 2.5 years after burial (see
38
39 386 [Table 1 and \[47\]](#)), due to the highly conductive grave fluid' producing a consistent
40
41 387 low resistance geophysical anomaly when compared to background site resistance
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43 388 values (Fig. 3). This agrees with other resistivity studies over simulated clandestine
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46
47 389 burials with similar monitoring time periods (see [\[26,52\]](#)). Recent collaborative
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49 390 research comparing the same monitoring experiment on three different University
50
51 391 sites [in contrasting soil types](#) has evidenced that conductivity measurements of grave
52
53 392 fluids could date the burial interval of a discovered clandestine grave in the field if a
54
55 393 conductivity meter was available and enough grave fluid was present (see [\[45\]](#)).
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3 394 However, this study showed that a naked cadaver would be very difficult to detect
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5 395 using fixed-offset electrical resistivity surveys after only four years of burial (Fig. 4)
6
7 396 and using ERI surveys after five years of burial (Fig. 5) respectively. The majority of
8
9 397 the grave fluids (other than that held by capillary pressure) would migrate away from
10
11 398 the cadaver and potentially result in a geophysical anomaly not being over the target,
12
13 399 and hence the subsequent search excavation team not finding the target, which would
14
15 400 be especially problematic in surveys within significant topographic variation (see
16
17 401 [1,30]. In contrast, the wrapped or clothed cadaver(s) essentially largely isolated the
18
19 402 target and its conductive grave fluids from the surrounding soil, giving a potential
20
21 403 barrier to electrical current. There was therefore a small and temporally varying high
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23 404 resistance anomaly, with respect to background site resistance values, identified over
24
25 405 the wrapped target location in the zero to three year monitoring data (see [47]), the
26
27 406 varying nature suggested to be caused by some leaking of grave fluids into the
28
29 407 surrounding soil. However, this paper detailing the four to six year monitoring data
30
31 408 showed a consistent large high resistance anomaly, when compared to background
32
33 409 site resistance values, to be present in both the fixed-offset and ERI electrical
34
35 410 resistivity datasets over the wrapped cadaver (see Figs. 4 and 5), this consistency
36
37 411 presumably due to most grave fluid at this time period being largely absent from the
38
39 412 survey area. Note that wrapping a body in plastic or clothing has also been reported
40
41 413 by others to slow decomposition [53] and inhibit micro-organism activity [51] which
42
43 414 therefore suggests a clandestinely buried body may be identifiable for longer if
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45 415 wrapped in woven PVC tarpaulin as compared to naked.
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54 417 Using all the resistivity datasets collected in the six year monitoring period, a
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56 418 graphical time-line diagram has been generated to show temporal resistivity anomaly
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3 419 variations (Fig. 7). In terms of optimally configuring fixed-offset resistivity
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5 420 equipment if the likely depth of burial is unknown, modern versions (eg. the
6
7 421 Geoscan™ RM-15 used in this study) have the capability to collect and digitally
8
9 422 record fixed-offset resistivity data at a variety of probe spacings almost
10
11 423 simultaneously at each sampling position (see [54] for forensic resistivity dataset
12
13 424 examples). This would therefore not significantly add to survey time if more than one
14
15 425 probe spacing data is collected and trace sample spacing could still be comparatively
16
17 426 small so that any potential loss in resolution is minimised. The forensic resistivity
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19 427 survey results in this paper are in sandy loam soil, with good forensic resistivity
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21 428 survey results also reported in coastal sand [36], chalky [26] and black earth [54] soil
22
23 429 types respectively, but relatively poor results in coarse pebble soil types [54].
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30 **FIG. 7. - position**

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34 433 *Secondly, B) - Could single profile GPR surveys successfully locate both simulated*
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36 434 *clandestine burials throughout the four to six year monitoring period? And which*
37
38 435 *dominant frequency antenna was optimal to detect them?* From the results shown in
39
40 436 this four to six year monitoring study, the naked cadaver was not able to be detected
41
42 437 on 2D GPR transverse profiles using either the 110 MHz or 900 MHz dominant
43
44 438 frequency antennae and was only poorly detectable by the 225 MHz dominant
45
46 439 frequency antennae in the autumn to winter datasets (Fig. 6A/B). This was in contrast
47
48 440 to the zero to three year monitoring period [47] and other studies undertaken on [47]
49
50 441 timescale (e.g. see [38,39,42]). The naked cadaver, however, was detectable as a
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52 442 deeper ½ hyperbolic reflection event in the 450 MHz 2D transverse profiles although
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54 443 this did not have high amplitudes (Fig. 6A/B). In contrast, the wrapped cadaver was
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3 444 detectable on 2D GPR profiles using all the frequencies trialled, namely the 110, 225
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5 445 and 450 MHz dominant frequency antennae (the 900 MHz antennae was not used
6
7 446 over this grave, but it is believed that the grave could have been detected with this
8
9 447 frequency based on the other frequency data). This was presumably still due to the
10
11 448 wrapping surface allowing stronger GPR reflections to be obtained, with the
12
13 449 decomposing naked cadaver attenuating a greater proportion of the GPR signal as
14
15 450 other authors have noted (e.g. see [42]). This radar absorption would be exacerbated
16
17 451 by the pig-chest cavity having collapsed during decomposition stages as noted in [47],
18
19 452 which is a probable explanation for the two GPR hyperbolae still present in 225 and
20
21 453 450 MHz dominant frequency data over the target location (Fig. 6A/B). 225 MHz
22
23 454 dominant frequency antennae was shown in this study to be preferable to the other
24
25 455 frequencies trialled (110, 450 and 900 MHz frequencies) in the 2D profiles due to a
26
27 456 detectable anomaly, target resolution and fewer non-target hyperbolae present in the
28
29 457 relative higher frequency data; note also forensic 225 MHz frequency radar surveys
30
31 458 also took less time in the field to acquire when compared to their higher frequency
32
33 459 versions. This could be an important factor for a forensic search team to consider if
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35 460 the proposed area is significant in size or if manpower and/or budget are limited. This
36
37 461 agrees with others (e.g. [42]) who also suggested that 2D GPR profiles should be
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39 462 collected in both orientations over a survey site if possible to have the best chance of
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41 463 detection.
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50 465 C) Thirdly, w*When was the optimal time (both up to six years post-burial and*
51
52 466 *seasonally) to undertake a forensic GPR or electrical resistivity geophysical search*
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54 467 *survey?* Clearly from the results shown in this study and others (e.g. [42]) the burial
55
56 468 style is key, it would be difficult to detect a naked burial after the first 18 months of
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3 469 | burial using the resistivity and GPR survey methods detailed here and in [47].
4
5 470 | However, note that other studies have shown favourable GPR survey results over
6
7 471 | much older burials in different ground conditions (eg. ([3,34,54,55]). ~~Using [37~~
8
9 472 | ~~Schultz & Martin 2012] four fold method for qualitatively determining a hyperbola~~
10
11 473 | ~~anomaly response over a simulated burial, i.e. excellent, good, poor and none, Figure~~
12
13 474 | ~~& graphically summarises this for the (A) wrapped and (B) naked cadaver~~
14
15 475 | ~~respectively.~~ Whilst there is a general reduction in hyperbola quality in both burial
16
17 476 | styles, with the naked cadaver being much more difficult to detect, there is a seasonal
18
19 477 | effect, with autumn and winter surveys, especially in years four to six post burial,
20
21 478 | generally better at resolving the targets. This has also been observed by authors
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23 479 | geophysically monitoring simulated clandestine burials on shorter time scales (e.g.
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25 480 | [42]).
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30 481
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32 482 | The resistivity surveys also showed a similar pattern, especially the fixed-offset
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34 483 | electrical resistivity surveys which, when following [46] methodology to numerically
35
36 484 | measure resistivity anomaly relative areas over time, consistently showed winter
37
38 485 | surveys were optimal (Fig. 9 Table 1). Each autumn to winter the anomalies over both
39
40 486 | the naked and wrapped cadavers increased in area and reduced in normalised standard
41
42 487 | deviation (SD) values whereas they were comparably smaller and had larger SD
43
44 488 | values in the summer months (Fig. 8). The naked cadaver's anomaly and the
45
46 489 | normalised SD of the datasets got progressively smaller over time, but the wrapped
47
48 490 | cadaver's relatively high resistance anomaly increased in size over the six year study
49
50 491 | period (Fig. 8). Temporally varying resistivity anomalies over fixed archaeological
51
52 492 | targets have also been reported by [56] who undertook time-lapse resistivity surveys
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54 493 | over UK Roman fortification defence ditches. This study therefore shows the cyclical
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1
2
3 494 nature of low winter/spring SD values and high summer/autumn SD values repeating
4
5 495 each year that was most probably due to the soil having reduced moisture content
6
7 496 during the warmer and dryer periods but, importantly, in a non-uniform manner for
8
9 497 this study site. Thus the 'noise' present within the geophysical data significantly
10
11 498 increased during these seasonal periods and effectively 'masked' the target(s). See
12
13 499 ([52] and [57] for detailed analysis of site soil moisture for the first two years of
14
15 500 burial.
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502 **FIG. 8. - position**

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504 *D) Finally, w*hen should a forensic geophysical survey be undertaken in a six year
505 search scenario? From this [and other studiesy \(e.g. 38-42,44\)](#), clearly the burial
506 style is still key; although the wrapped grave was initially harder to detect with
507 electrical resistivity surveys (as shown in [47]), in this paper it is relatively easier to
508 detect after four to six years of burial (Fig. 7). The wrapping also makes the target
509 easier to find with GPR as the wrapping makes a good reflective target ([Table 1](#)). So
510 although wrapping may help to conceal a body in some ways (for example, it may
511 trap scent and prevent decompositional fluids leaching into the soil), it may also make
512 a body easier to find geophysically. If the burial style is not known, then it is
513 suggested that both electrical and GPR surveys be undertaken to have the best chance
514 of successful detection. Note a naked cadaver would be progressively more difficult
515 to find after 18 months of burial as shown in this [\(Table 1\) and other studies](#) (see [\[38-](#)
516 [42,44\]Figs. 8 and 9](#)), and therefore other complementary methods should be trialled
517 (e.g. search cadaver dogs).
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3 519 | This study also ~~shows~~ reinforces other research (see e.g. 38-42,44,56) the importance
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5 520 | of when a forensic geophysical survey should be conducted within the year,
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7 521 | seasonality has shown to be surprisingly important, and, if operational time permits,
8
9 522 | then geophysical surveys should be undertaken in winter to have the best chance of
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11 523 | target detection success. If a past forensic geophysical search was unsuccessful,
12
13 524 | perhaps the results should be reviewed in terms of seasonality and perhaps re-
14
15 525 | surveyed if the original survey season was unfavourable. If there is a time-restricted
16
17 526 | element to the forensic search, then the season of surveying should be undertaken and
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19 527 | an appropriate alternative search method should be chosen if necessary.
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25 529 | From this long-term simulated grave monitoring study and comparing results from
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27 530 | [24,27],29,38-42, 44,57-60], we still recommend that forensic geophysical surveys
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29 531 | should be undertaken prior to other, more invasive search methods (e.g. metal
30
31 532 | detectors, soil/methane probes and cadaver dog probes). Any resulting soil
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33 533 | disturbances from these surveys would lead to more false positives for the resulting
34
35 534 | geophysical surveys, as found during the [29] forensic resistivity search. Once
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37 535 | anomalous geophysical areas within the survey area are identified, these should be
38
39 536 | prioritised and then subjected to more detailed scientific investigations, which
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41 537 | includes geophysical surveys (e.g. 2D ERI profiles, higher frequency 2D/3D GPR
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43 538 | surveys), cadaver dogs, invasive probing, etc. See [11] for other geoscience search
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45 539 | methods and suggested phased investigative approaches.
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3 542 **Conclusions and further work**
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7 544 Geophysical long-term monitoring survey results over the simulated clandestine
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10 545 | burials shown in this study and by others in different soil types should be used both to
11
12 546 | assist forensic search investigators to use the appropriate search technique and
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14 547 | equipment configuration, and indeed as a reference to allow comparison of data
15
16 548 | collected by forensic search investigators looking for similar clandestine burials of
17
18 549 | murder victims.
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23 551 *A buried 'naked' victim* within a clandestine burial, if shallowly buried, should be
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25 552 | able to be located within the first 4 years of burial using fixed-offset twin electrode
26
27 553 | electrical resistivity surveys. If the burial depth is unknown, the use of wider
28
29 554 | electrode separations in addition to the standard-most frequently used 0.5 m spacing is
30
31 555 | recommended. Resistivity surveys are also recommended to be undertaken in clay-
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33 556 | rich soils over GPR surveys due to the likelihood of highly conductive 'leachate'
34
35 557 | being retained in the surrounding soil and GPR experiencing poor penetration depths
36
37 558 | in these soil types. However after this time period a naked victim would become
38
39 559 | progressively more difficult to locate using electrical methods, with the majority of
40
41 560 | the decompositional fluids migrating away from the target, depending upon the soil
42
43 561 | type. However, ERI 2D profiles could potentially still locate naked victims up to five
44
45 562 | years of burial if sited over it. 110 – 225 MHz dominant frequency GPR surveys
46
47 563 | could detect it-targets well up to 18 months of burial, then 225 MHz frequency poorly
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49 564 | in winter months up to five years of burial due to decomposition, although skeletal
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51 565 | material may still be imaged depending on target(s) depth and specific site conditions.
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53 566 | If time and manpower availability permits then winter surveys should be undertaken.
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5 568 A buried 'wrapped' or clothed victim within a clandestine burial, if shallowly buried,
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7 569 should be able to be located using both fixed-offset electrical resistivity and ERI 2D
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9 570 Profile surveys throughout the six year monitoring period; in fact in this study it
10
11 571 became progressively easier to detect the wrapped cadaver as the burial period
12
13 572 extended. Medium (225-450 MHz) dominant frequency GPR antennae were deemed
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15 573 optimal frequency for detection due to good target resolution as other authors have
16
17 574 evidenced (e.g. [41-42]); less non-target anomalies and data acquisition speed,
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19 575 although 110 MHz and 450 MHz frequency antennae data also resolved the wrapped
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21 576 grave throughout the study period, most probably due to the 'wrapping' producing a
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23 577 good reflective contrast. If time and manpower availability permits then winter
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25 578 surveys should be undertaken.
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32 580 This study site will be continued to be monitored annually to discover *at what time*
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34 581 period after burial will geophysical surveys not be able to determine the location of a
35
36 582 clandestine burial. Organic, inorganic and other analytical measurements are
37
38 583 currently being undertaken to examine what may be causing the variability in grave
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40 584 'soilwater' conductivity after burial with preliminary results looking promising [61].
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45 586 Further analysis of the geophysical data will also be undertaken; both to determine if
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47 587 there are diagnostic GPR signal spectra for clandestine burials versus background
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49 588 signals and to determine if both GPR and resistivity datasets can be simultaneously
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51 589 inverted numerically to quantify anomaly location(s), sizes and to quantitatively
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53 590 combine these two geophysical search techniques.
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3 592 | This experimental methodology should be repeated on similar time scale in other,
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5 593 | contrasting soil types, in order to determine if soil type is a major factor in the ability
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7 594 | of forensic geophysical surveys to successfully locate a clandestine burial. On a
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9 595 | longer time scale, it is planned that the experiment will be repeated using human
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11 596 | cadavers rather than pig analogues, as this may be an important variable to consider.
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608

609 **References:**

610

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

614

615 | 2. Larson DO, Vass A A, Wise M. Advanced scientific methods and procedures in the
616 | forensic investigation of clandestine graves. J Contemp Crim Justice 27 2011;27:149–
617 | 82.

618

619 | 3. Davenport GC. Remote sensing applications in forensic investigations. Hist Arch
620 | 2001;35:87–100.

621

622 | 4. Killam EW. The detection of human remains. Springfield: Charles C Thomas,
623 | 2004.

624

625 | [5. Dupras TL, Schultz JJ, Wheeler SM, Williams LJ. Forensic recovery of human
626 | remains: archaeological approaches. 2nd ed, Boca Raton, FL: CRC Press, 2011.](#)

627

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

630

- 1
2
3 631 | [7.](#) Lasseter A, Jacobi KP, Farley R, Hensel L. Cadaver dog and handler team
4 capabilities in the recovery of buried human remains in the Southeastern United
5 632 States. *J For Sci* 2003;48:1–5.
6
7 633
8
9 634
10
11 635 | [8.](#) Pye K, Croft, DJ. *Forensic Geoscience: Principles, Techniques and Applications.*
12 London: Geol Soc London Spec Pub 232, 2004.
13 636
14
15 637
16
17 638 | [9.](#) Ruffell A, McKinley J. *Forensic geoscience: applications of geology,*
18 *geomorphology and geophysics to criminal investigations.* *Earth Sci Rev*
19 639 2005;69:235–47.
20
21 640
22
23 641
24
25 642 | [10.](#) Ruffell A, McKinley J. *Geoforensics.* Chichester: Wiley, 2008.
26
27 643
28
29 644 | [11.](#) Pringle JK, Ruffell A, Jervis JR, Donnelly L, McKinley J, Hansen J, Morgan R,
30 *Pirrie D, Harrison M. The use of geoscience methods for terrestrial forensic searches.*
31 645 *Earth Sci Rev* 2012;[a](#);114:108-23.
32
33 646
34
35 647
36
37 648 | [12.](#) Davenport GC, Griffin TJ, Lindemann JW, Heimmer D. Geoscientists and law
38 *enforcement officers work together in Colorado.* *Geotimes* 1990;35:13–5.
39 649
40
41 650
42
43 651 | [13.](#) Brilis GM, Gerlach CL, van Waasbergen RJ. Remote sensing tools assist in
44 *environmental forensics. Part I. Digital tools—traditional methods.* *Env For*
45 652 2000a;1:63–7.
46
47 653
48
49 654
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 655 | [14.](#) Brilis GM, van Waasbergen RJ, Stokely PM, Gerlach CL. Remote sensing tools
4 |
5 656 | assist in environmental forensics. Part II. Digital tools. *Env For* 2000b;1:1–7.
6 |
7 657 |
8 |
9 |
10 658 | [15.](#) Hunter J, Cox M. *Forensic archaeology: advances in theory and practice.*
11 |
12 659 | Abingdon: Routledge, 2005.
13 |
14 660 |
15 |
16 661 | [16.](#) Dickinson DJ. The aerial use of an infrared camera in a police search for the body
17 |
18 662 | of a missing person in New Zealand. *J For Sci Soc* 1976;16:205–11.
19 |
20 663 |
21 |
22 |
23 664 | [17.](#) Ruffell A, McKinley J. Forensic geomorphology. *Geomorph* 2014;206:14-22.
24 |
25 665 |
26 |
27 666 | [18.](#) Owsley DW. Techniques for locating burials, with emphasis on the probe. *J For*
28 |
29 667 | *Sci* 1995;40;735–40.
30 |
31 668 |
32 |
33 |
34 669 | [19.](#) Ruffell A. Burial location using cheap and reliable quantitative probe
35 |
36 670 | measurements. *For Sci Int* 2005a;151:207-11.
37 |
38 671 |
39 |
40 672 | [20.](#) Hunter J, Simpson B, Sturdy Colls C, *Forensic approaches to buried remains*
41 |
42 673 | (essential forensic science). Chichester: Wiley, 2013.
43 |
44 674 |
45 |
46 |
47 675 | [21.](#) Reynolds JM. *An introduction to applied and environmental geophysics*, 2nd ed,
48 |
49 676 | Chichester: Wiley-Blackwell, 2011.
50 |
51 677 |
52 |
53 |
54 678 | [22.](#) Mellet JS. Location of human remains with ground penetrating radar. In:
55 |
56 679 | Hanninen, P, Autio S, editors. [Proceedings of the Fourth International Conference on](#)
57 |
58 |
59 |
60 |

- 1
2
3 680 [Ground Penetrating Radar GPR](#), 1992 Jun 8-13; Rovaniemi, Geological Survey of
4
5 681 Finland Special Paper 16;359–65.
6
7 682
8
9
10 683 [23. Calkin SF, Allen RP, Harriman MP. Buried in the basement – geophysics role in a](#)
11
12 684 [forensic investigation. Proceedings of the symposium on the application of](#)
13
14 685 [Geophysics to engineering and environmental](#) problems; 1995, Denver: Env Eng
15
16 686 Geophys Soc;397–403.
17
18 687
19
20
21 688 [24. Nobes DC. The search for “Yvonne”:](#) a case example of the delineation of a
22
23 689 [grave using near-surface geophysical methods. J For Sci 2000;45:715–21.](#)
24
25 690
26
27
28 691 [25. Scott J, Hunter JR. Environmental influences on resistivity mapping for the](#)
29
30 692 [location of clandestine graves. In: Pye K, Croft DJ, editors. Forensic Geoscience:](#)
31
32 693 [Principles, Techniques and Applications. London: Geol Soc London Spec Pub](#)
33
34 694 [2004;232:33–8.](#)
35
36 695
37
38
39 696 [26. Cheetham P. Forensic geophysical survey. In: Hunter J, Cox M, editors. Forensic](#)
40
41 697 [Archaeology: Advances in Theory and Practice, Abingdon: Routledge, 2005;62–95.](#)
42
43 698
44
45
46 699 [27. Ruffell A. Searching for the IRA “disappeared”:](#) Ground Penetrating radar
47
48 700 [investigation of a churchyard burial site. J For Sci 2005;50:1430-5.](#)
49
50 701
51
52 702 [28. Schultz JJ. Using ground-penetrating radar to locate clandestine graves of](#)
53
54 703 [homicide victims: forming forensic archaeology partnerships with law enforcement.](#)
55
56 704 [Homicide Studies 2007;11:15-29.](#)
57
58
59
60

1
2
3 705

4
5 706 | [29.](#) Pringle JK, Jervis JR. Electrical resistivity survey to search for a recent
6
7 707 | clandestine burial of a homicide victim, UK. For Sci Int 2010;202(1-3):e1-7.

8
9
10 708

11 709 | [30.](#) Novo A, Lorenzo H, Ria F, Solla M. 3D GPR in forensics: finding a clandestine
12
13 710 | grave in a mountainous environment. For Sci Int 2011;204:134-8.

14
15
16 711

17
18 712 | [31.](#) Schultz JJ. The application of GPR for forensic grave detection. In: Dirkmaat DC,
19
20 713 | [editors. A companion to forensic anthropology, Hoboken, NJ: Blackwell, 2012, p.85-](#)
21
22 714 | [100.](#)

23
24
25 715

26
27 716 | [32.](#) Ruffell A, Pringle JK, Forbes S. Search protocols for hidden forensic objects
28
29 717 | beneath floors and within walls. For Sci Int 2014;237:137-45.

30
31
32 718

33
34 719 | [33.](#) France DL, Griffin TJ, Swanburg JG, Lindemann JW, Davenport GC, Trammell
35
36 720 | V. et al. A multidisciplinary approach to the detection of clandestine graves. J For Sci
37
38 721 | 1992;37:1445–58.

39
40
41 722

42
43 723 | [34.](#) Strongman KB. Forensic applications of ground penetrating radar. In: Pilon J,
44
45 724 | editor. Ground Penetrating Radar, Ottawa: Geological Survey of Canada Paper 90-4,
46
47 725 | 1992;203–11.

48
49
50 726

51
52 727 | [35.](#) Freeland RS, Miller ML, Yoder RE, Koppenjan SK. Forensic applications of
53
54 728 | FMCW and pulse radar. J Env Eng Geophys 2003;8:97–103.

55
56
57 729

- 1
2
3 730 | [36.](#) Pringle JK, Holland C, Szkornik K, Harrison M. Establishing forensic search
4
5 731 | methodologies and geophysical surveying for the detection of clandestine graves in
6
7 732 | coastal beach environments. For Sci Int 2012;219:e29-e36.
8
9 733 |
10
11 734 | [37.](#) Pringle JK, Wisniewski K, Giubertoni M, Cassidy NJ, Hansen JD, Linford NJ,
12
13 | [Daniels RM. The use of magnetic susceptibility as a forensic search tool. For Sci Int](#)
14 735 | [2015a;246:31-42.](#)
15
16 736 |
17
18 737 |
19
20 738 | [38.](#) Schultz JJ, Collins ME, Falsetti AB. Sequential monitoring of burials containing
21
22 739 | large pig cadavers using ground-penetrating radar. J For Sci 2006;51:607–16.
23
24 740 |
25
26 741 | [39.](#) Schultz JJ. Sequential monitoring of burials containing small pig cadavers using
27
28 742 | ground-penetrating radar. J For Sci 2008;53:279–87.
29
30 743 |
31
32 744 | [40.](#) Pringle JK, Jervis J, Cassella JP, Cassidy NJ. Time-lapse geophysical
33
34 745 | investigations over a simulated urban clandestine grave. J For Sci 2008;53:1405-17.
35
36 746 |
37
38 747 | [41.](#) Schultz JJ, Martin MM. Controlled GPR grave research: Comparison of reflection
39
40 748 | profiles between 500 and 250 MHz antennae. For Sci Int 2011;209:64-9.
41
42 749 |
43
44 750 | [42.](#) Schultz JJ, Martin MM. Monitoring controlled graves representing common burial
45
46 751 | scenarios with ground penetrating radar. J App Geophys 2012;83:74-89.
47
48 752 |
49
50 753 | [43.](#) Schotmans EMJ, Fletcher JN, Denton J, Janaway RC, Wilson AS. Long-term
51
52 754 | effects of hydrated lime and quicklime on the decay of human remains using pig
53
54
55
56
57
58
59
60

1
2
3 755 cadavers as human body analogues: Field experiments. For Sci Int 2014a;238:141.e1-
4
5 756 e13.

6
7 757

8
9
10 758 | [44](#). Molina CM, Pringle JK, Saumett M, Hernandez O. Preliminary results of
11
12 759 | sequential monitoring of simulated clandestine graves in Colombia, South America,
13
14 760 | using ground penetrating radar and botany.-[For Sci Int 2015;248:61-70](#).

15
16 761

17
18 762 | [45](#). Pringle JK, Cassella JP, Jervis JR, Williams A, Cross P, Cassidy NJ. Soilwater
19
20 763 | conductivity analysis to date and locate clandestine graves of homicide victims. J For
21
22 764 | Sci in press.

23
24 765

25
26 766 | [46](#). Jervis JR, Pringle JK. A study of the affect of seasonal climatic factors on the
27
28 767 | electrical resistivity response of three experimental graves. J App Geophys
29
30 768 | 2014;108:53-60.

31
32 769

33
34 770 | [47](#). Pringle JK, Jervis JR, Hansen JD, Cassidy NJ, Jones GM, Cassella JP.
35
36 771 | Geophysical monitoring of simulated clandestine graves using electrical and Ground
37
38 772 | Penetrating Radar methods: 0-3 years. J For Sci 2012**b**;57:1467-86.

39
40 773

41
42 774 | [48](#). Manhein MH. Decomposition rates of deliberate burials: a case study of
43
44 775 | preservation. In: Haglund WD, Sorg MH, editors. Forensic taphonomy: the post-
45
46 776 | mortem fate of human remains, Boca Raton, [FL](#): CRC, 1996;469–81.

47
48 777

49
50 778 | [49](#). Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-
51
52 779 | Geiger climate classification. Hydro Earth Sys Sci 2007;11:1633–44.

53
54
55
56
57
58
59
60

1
2
3 7804
5 781 | [50.](#) Vass AA, Bass WM, Wolt JD, Foss JE, Ammons JT. Time since death
6
7 782 | determinations of human cadavers using soil solution. *J For Sci* 1992;37:1236–53.
89
10 78311 784 | [51.](#) Carter DO, Tibbett M. Cadaver decomposition and soil: processes. In: Tibbett M,
12
13 785 | Carter DO, editors. *Soil Analysis in Forensic Taphonomy: Chemical and Biological*
14
15 786 | *Effects of Buried Human Remains*. Boca Raton: CRC Press, 2009;29–52.
16
17 78718
19
20 788 | [52.](#) Jervis JR, Pringle JK, Tuckwell GT. Time-lapse resistivity surveys over simulated
21
22 789 | clandestine burials. *For Sci Int* 2009;192:7-13.
23
24 79025
26
27 791 | [53.](#) Rodriguez WC. Decomposition of buried and submerged bodies. In: Haglund
28
29 792 | WD, Sorg MH, editors. *Forensic Taphonomy: The Postmortem Fate of Human*
30
31 793 | *Remains*. Boca Raton: CRC Press, 1997;459–68.
32
33 79434
35
36 795 | [54.](#) Hansen JD, Pringle JK, Goodwin J. GPR and bulk ground resistivity surveys in
37
38 796 | graveyards: locating unmarked burials in contrasting soil types. *For Sci Int*
39
40 797 | 2014;237:e14-e29.
41
42 79843
44
45 799 | [55. Bevan BW. The search for graves. *Geophysics* 1991;56:1310–9.](#)
46
47 80048
49 801 | [56.](#) Clark AJ. *Seeing beneath the soil: prospecting methods in archaeology*, 2nd rev.
50
51 802 | ed. New York: Routledge, 1996.
52
53 80354
55
56
57
58
59
60

1
2
3 804 | [57.](#) Jervis JR. The detection of clandestine graves using electrical resistivity surveys:
4 results from controlled experiments and a case study (PhD dissertation). Keele: Keele
5 University, 2011.
6
7
8

9
10 807

11 808 | [58.](#) Ellwood BB, Owsley DW, Ellwood SH, Mercado-Allinger PA. Search for the
12 grave of the hanged Texas gunfighter, William Preston Longley. Hist Arch
13
14 809
15
16 810 1994;28:94-112.
17

18
19 811

20 812 | [59.](#) Ruffell A, McCabe A, Donnelly C, Sloan B. Location and assessment of an
21 historic (150-160 years old) mass grave using geographic and ground penetrating
22
23 813
24
25 814 radar investigation, NW Ireland. J For Sci 2009;54:382-94.
26

27
28 815

29 816 | [60.](#) Powell K. Detecting human remains using near-surface geophysical instruments.
30 Expl Geophys 2004;35:88–92.
31
32 817

33
34 818

35
36 819 | [61.](#) Blom G, Davidson A, Pringle J, Williams A, Lamont A, Cassella JP. Chemical
37 markers for the detection of clandestine graves – development of a complimentary
38
39 820
40
41 821 technique for forensic geophysics? Recent Work in Arch Geophys and For Geosci:
42
43 822 Future Horizons Conf, Geol Soc London, 2-3 December, 2014.
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3 825 **FIGURE CAPTIONS:**
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7 827 **FIG. 1.** (A) Map of survey area (dashed rectangle) with graves, L1/2 GPR and ERI
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9 828 2D profile lines, lysimeter positions and UK location map all shown (inset). (B)
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11 829 Study site, (C) naked pig grave, (D) wrapped pig grave, (E) pig lysimeter grave and
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14 830 (F) soil fluid measurement photographs respectively. Modified from [47].
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18 832 **FIG. 2.** Summary of monthly study site statistics of total rainfall (bars) and average
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20 833 temperature (line) data at 0.3 m bgl (below ground level), measured over the four to
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22 834 six year study period. Dashed average temperature line is for zero to three years
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25 835 survey period [47] shown for comparison.
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29 837 **FIG. 3.** (A) Measured pig leachate (diamonds) and background (triangles) soil-water
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31 838 fluid conductivity values over the 6-year survey period; 4-6 years to the right of the
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33 839 vertical dotted line. (B) Measured soil-water conductivity versus accumulated degree
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35 840 day (ADD) plot produced from (A) by summing average daily 0.3 m bgl after burial
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37 841 temperatures (see text). Best-fit linear correlation formulae and confidence (R2)
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39 842 values are also shown. Modified from [47].
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45 844 **FIG. 4.** Fixed-offset processed electrical resistivity datasets for the four to six year
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47 845 study period (year and season shown). Red, green and blue rectangles indicate
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49 846 positions of naked pig, empty and wrapped pig graves respectively (see Fig. 1A).
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54 848 **FIG. 5.** Individually inverted 2D Electrical Resistivity Imaging (ERI) Wenner array
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56 849 (0.5 m spaced electrode) profiles for the four to six year study period (year and season
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3 850 shown); model inversion errors (RMS) for the fifth iterations are indicated. Positions
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5 851 of naked pig, empty and wrapped pig graves are also shown (dashed lines). See Fig.
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7 852 1A (ERI/ERI') for location.
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11 854 **FIG. 6(A).** Key sequential processed 110, 225, 450 and 900 MHz dominant

12 855 frequency GPR profiles for ~~the four to six year study period~~ 39 – 54 post-burial

13 856 months (year and season shown) that bisect the naked and wrapped pig graves

14 857 respectively (Fig. 1A for location).
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24 859 **FIG. 6(B).** Key sequential processed 110, 225, 450 and 900 MHz dominant

25 860 frequency GPR profiles for 57 – 72 post-burial months ~~the four to six year study~~

26 861 ~~period~~ (year and season shown) that bisect the naked and wrapped pig graves

27 862 respectively (Fig. 1A for location).
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35 864 **FIG. 7.** Summary qualitative analysis plot of resistivity data over the complete six

36 865 year survey period with this paper 4-6 year survey period to the right of the vertical

37 866 dashed lines (see key and text). Modified from [47].
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44 868 ~~**FIG. 8.** Summary qualitative analysis plots of GPR data collected over the complete~~

45 869 ~~six year survey period with this paper 4-6 year survey period to the right of the~~

46 870 ~~vertical dashed line (see key and text).~~
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52 872 **FIG. 8.** Summary quantitative analysis plots of fixed-offset resistivity data collected

53 873 over the complete six year survey period with this paper 4-6 year survey period to the

54 874 right of the vertical dashed line. (A) Standard deviations (SD) for each survey, note
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875 SD values are highest in late summer; residual volume analysis of (B) naked pig

876 | cadaver and (C) wrapped pig cadaver (see text). Modified from [46].

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3 879 **TABLE CAPTION:**

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7 881 **TABLE 1.** Summary of geophysical surveys and their respective geophysical
8 anomalies data collected detailed in this paper study (4-6 year results below horizontal
9 line). [^]GPR surveys conducted the day after respective survey dates and groundwater
10 conductivity measurements collected the day before respective survey dates. ⁺Burial
11 date was 7th December 2007. *ADD date based on average daily site temperatures at
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18 886 0.3 m bgl (see [47]).
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