Comparisons of Magnetic and Electrical Resistivity Surveys Over Simulated Clandestine Graves in Contrasting Burial Environments

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ABSTRACT

It can be crucial to know the effectiveness of particular geophysical detection techniques when trying to locate clandestine burials of murder victims. . Unlike in archaeology, there has been limited forensic research with regard to optimum methodologies, with most emphasis to-date on metal detectors and Ground Penetrating Radar by forensic search teams. This may not be suitable in certain soil types, non-metal targets or in significant search areas. Therefore in this study, magnetic and electrical resistivity detection techniques have been utilised over different-aged (0.25 -1 year) simulated clandestine burials with no buried metal, in contrasting depositional environments. These environments included semi-rural, urban, woodland and parkland, the parkland Medieval grave site acting as a control.

The magnetic surveys showed mixed success of detecting clandestine burials. Elevated magnetic gradient readings, with respect to background values, were observed over very shallow burials, whereas deeper burials displayed a reduction in gradient and/or no associated magnetic anomalies. Magnetic anomalies were observed over surface-burials and validated by simple 2D forward modelling. Magnetic anomalies were also observed in the control dataset. Electrical resistivity surveys produced anomalies over all the simulated burial positions, including surface burials, but it did not produce anomalies at the control site.

Laboratory analysis of simulated grave 'fluid' showed an overall increase in iron levels over a year post-burial (from xx to xx) which may account for the observed

magnetic anomaly variation. There was also a corresponding increase in grave 'fluid' conductivity which was interpreted to cause the observed resistivity anomalies.

Study results have important implications for use of geophysical techniques when searching for clandestine burials. Local depositional environment, soil type, likely style of burial and search area size should all be considered when choosing forensic geophysical detection techniques. Geophysical data could locate a primary deposition site even though no physical evidence remains.

INTRODUCTION

Non-invasive, near-surface geophysical techniques are being increasingly utilised in forensic and criminal investigations to assist in locating clandestine burials of murder victims (Nobes, 2000; Buck, 2003; Ruffell & McKinley, 2005; Ruffell & McKinley, 2009). To date, the most commonly used technique after metal detectors (see Rezos et al. 2010) is Ground Penetrating Radar or GPR (Davis *et al.* 2000; Witten *et al.* 2000; Koppenjan *et al.* 2003; Ruffell, 2005). However, certain site specific conditions such as water-logged and/or clay rich soils as well as significant search areas can render GPR unsuitable for some forensic search purposes (Fenning & Donnelly, 2004; Pringle & Jervis, in press). As potential alternative geophysical search techniques for modern and ancient burials, electrical and magnetic methods have proven useful in identifying anomalous areas for follow-up investigation, even when metallic objects were not present in the graves (Evans and Heller, 2003; Linford, 2004; Cheetham, 2004; Pringle *et al.* 2008; Jervis *et al.* 2009a,b). However, there is a lack of published information relating to magnetic surveys and comparisons with electrical resistivity methods from both simulated and forensic case clandestine grave studies.

The few documented clandestine burial studies using magnetic and bulk ground resistivity techniques showed mixed detection success (Buck, 2003; Witten, 2004; Pringle *et al.* 2008). For magnetic surveys, in cases when there was successful detection without the presence of metallic objects, the potential cause(s) of the

magnetic anomaly were uncertain and required further investigation. Potential causes cited included secondary microbial action on decomposing tissue and associated fluids (Linford, 2004), magnetite crystals forming from magnetotactic bacteria (Fassbinder and Irlinger, 1994), and pH/Eh (reduction potential) changes caused by anaerobic bacteria action during decomposition of organic material (Linford, 2004, Schmidt, 2007). Other authors have suggested that increased magnetic signals may simply be due to soil disturbance and the re-orientation of magnetised grains or sediment with detrital remnant magnetisation (Gaffney & Gater, 2003). For resistivity surveys, anomalous ground resistivity values have been theorised to be caused by factors including varying ionic input from decomposition fluids (Vaas *et al.* 1992; Jervis *et al*, 2009a), ground disturbance (Gaffney & Gater, 2003), and relative conductivity of buried material (Jervis *et al*, 2009b; Pringle et al, 2010). Despite this research, understanding of the limitations and controls on specialist geophysical equipment and their response to near-surface buried materials is currently extremely limited.

This research compares and contrasts magnetic and bulk ground resistivity methods from an archaeological-forensic perspective and assesses their effectiveness as geoforensic techniques for locating simulated clandestine burials in a variety of depositional environments. Furthermore, we aim to improve the understanding of controls and potential technique limitations. Project objectives were to: 1) collect magnetic data over sites with contrasting depositional environments that contained different simulated clandestine burial target types, ages, sizes, and depths of burial; 2) characterise the bedrock and soil type and soil moisture content at each site; 3) extract

grave 'fluid' and background soil-water over a one year period on one site to analyse and determine if any temporal analytical change could be quantified; 4) compare and contrast the collected datasets and finally ; 5) determine where and when (post-burial), and potentially explain why magnetic and electrical resistivity surveys may (or may not) be optimal to detect clandestine grave sites in certain depositional environments.

METHODOLOGY

Human Analogues (*Sus Domestica*)

Due to the Human Tissue Act (2004), the use of human material is prevented in the UK. Permission to use pig (*Sus domestica*) cadavers instead was obtained from the UK Department for Environment, Food and Rural Affairs (DEFRA) under Regulation (EC) No. 1774/2002.

The justification for the use of pig cadavers as human analogues stems from research that has identified similarities in fatty acid compositions between human and pig adipose tissue, as well as similar-sized organs, body tissue:fat ratios, skin and hair types (Carter & Tibbett, 2009). Furthermore, similar decomposition rates and products suggest pigs are suitable analogues to represent human decomposition for this study (Carter & Tibbett, 2009; Notter *et al.* 2009).

STUDY SITE LOCATIONS

These are now separately described, see Table 1 for site summaries. Note no metal components were buried with the simulated clandestine grave material.

Semi-Rural Environment: Keele University, Staffordshire, UK

The study site was located in a restricted part of Keele University campus and is representative of a sheltered, semi-rural setting (Fig. 1a). Keele is situated in the West Midlands of the UK, is ~ 200 m above sea level and has a temperate climate with a monthly average rainfall and temperature of 75 mm and 9 °C respectively. The site comprised a semi-grassed area that was ~25 m x ~25 m, surrounded by deciduous immature trees and shrubs, with a topographic slope that dips 3° to the south-east (Fig. 1b, c). Local borehole records and shallow excavations show a sandy loam topsoil with some artificial materials present (brick, concrete and metal fragments). The underlying Carboniferous Springpool Sandstone bedrock of the Keele Group is present at ~2.6 m below ground level (bgl). The micaceous-rich sandstone is relatively high in iron minerals (predominantly weathered haematite), which are also abundant within the overlying clay horizon-rich soils.

Simulated clandestine graves included a blank grave, an unwrapped pig cadaver and a pig cadaver wrapped in plastic sheeting (Fig. 1c). Each cadaver weighed ~80 kg and had been dead for less than 24 hours prior to burial. The graves were ~1.5 m long, ~0.75 m wide and ~0.6 m bgl (bgl depths based on average discovered clandestine graves, see Manhein, 1996) within a 14 m x 5 m survey area. Following grave excavation and pig emplacement, the graves were backfilled with the same soil and, the grass-turf replaced on the 7th December 2007 (Table 1). A third pig cadaver was buried outside of the survey area with a lysimeter installed to extract grave 'fluid'. A lysimeter was also placed outside the survey area to extract background soil-water to provide a control (see Jervis *et al*. 2009a; Pringle et al. 2010 for details).

Urban Environment: Staffordshire University Crime Scene House, Staffordshire, UK

This study site was located in the garden of the Crime Scene House on the Staffordshire University, Stoke campus and is representative of an urban setting (Fig. 2a). Situated in the West Midlands of the UK, it is ~ 100 m above sea level and has a temperate climate, with a monthly average rainfall and temperature of 56 mm and 13 ºC respectively. The survey site comprised a grassed area that was ~40 m x 10 m, surrounded by mature hedges and deciduous trees on three sides and a raised car park and the Crime Scene House on the other side (Fig. 2b, c). It also had a significant topographic slope dipping ~10º to the south. Local borehole records and shallow excavations show clay loam soil with ~25% of the top 1 m bgl comprising artificial materials of clayey ash, bricks, concrete and coal fragments that overlies sand and

alluvium deposits from the nearby River Trent. The Carboniferous Middle Coal Measures bedrock is encountered ~10 m bgl (see Pringle *et al.* 2008). The near-surface soil is highly variable across the study site and is designated 'made ground'.

The simulated clandestine grave comprised an unwrapped pig cadaver emplaced in a ~1.1 m long, ~0.6 m wide and ~0.6 m bgl pit within a 4.5 m x 8 m survey area (Fig. 2c). The cadaver was a ~30 kg pig with internal organs removed. Following the grave excavation and pig emplacement, the graves were backfilled with the same soil and, the grass turf replaced on the 15th March 2007 (Table 1).

Woodland Environment: Lincoln University, Lincolnshire, UK

The study site was located in a restricted part of Lincolnshire University, Riseholme campus and is representative of a sheltered, rural deciduous woodland setting (Fig. 3a). It is situated in the East Midlands of the UK, ~70 m above sea level and has a temperate climate, with a monthly average rainfall and temperature of ~130 mm and ~13 ℃ respectively. The site comprised a grass-free area that was 30 m x 100 m, with a flat lying topography (Fig. 3b, c). Shallow excavations show a layer of organic leaf litter followed by sandy loam that overlies a silt horizon at ~0.5 m bgl. The underlying bedrock is the Jurassic Lincolnshire Limestone.

A variety of clandestine graves were simulated, including four individual graves and three multiple cadaver (mass) graves with unwrapped cadavers (Fig. 3a). The cadavers were ~1.5 kg, ~3.5 kg, ~25 kg, ~50 kg and ~25 kg in weight. The grave dimensions varied according to the pig cadaver size but remained ~ 0.5 m bgl within a 10 m x 8 m survey area. Following grave excavation and cadaver emplacement, the graves were backfilled with the same soil and, the grass turf replaced on the 28th April 2007 (Table 1). Five further cadavers of the same weight as the individual buried cadavers were also placed on the ground surface (Fig.3a, c).

Urban Environment & Control: Hulton Abbey, Staffordshire, UK

The study site was located within a landscaped municipal park in Abbey Hulton, Stoke-on-Trent and represents an ancient analogue within an urban setting, containing an unmarked medieval monk cemetery (Fig. 4a). Abbey Hulton is situated in the West Midlands, UK and is ~5 km from the Staffordshire University test site. The site comprised a ~500 m x ~1000 m plot, with landscaped grassed areas, small deciduous copses and an uneven topography (Fig. 4b). Previous archaeological excavations onsite (Klemperer & Boothroyd, 2004) reveal a clay loam soil containing a significant amount of artificial materials. The Lower Carboniferous Coal Measures bedrock is encountered at ~20 m bgl. Foundations from a now-demolished school are still present onsite. There are also a number of above-ground abbey wall remnants that are in close proximity to the survey area (Fig. 4b, c).

There are an estimated 100 monk graves onsite and ~ 12 high status individuals, the latter buried within the old abbey walls at unknown depths, based on the previous archaeology excavations (Klemperer & Boothroyd, 2004). The monks were buried between 1219 and 1538 A.D (Klemperer & Boothroyd, 2004).

Keele University Grave 'Fluid' Analysis

Grave 'fluid' and background soil-water samples from the Keele site were extracted and immediately measured for conductivity (see Jervis *et al.* 2009b; Pringle et al. 2010). Subsequent, Inductivity-Coupled Plasma – Optical Emission Spectrometry (ICP-OES) was undertaken on samples after the survey was completed (see Brooks *et al.* 2006 for details). In this study, 1.5 ml of each sample was taken and put into an Eppendorf tube and centrifuged at 4000 rpm for 15 minutes to remove any potential soil particles that may have been present. A 1 ml centrifuged sample of each was taken and added to an ICP tube, diluted with 5 ml of de-ionised water and acidified with 0.6 ml of Nitric Acid, to give a final 10% acid concentration sample. Samples taken up to 335 days post burial from the site were run on a Varian™ Vista-MPX CCD Simultaneous ICP-OES instrument, using a Varian™ SPS3 auto-sampler and analysed for 39 common elements, using ICP Expert™ v.4.0 software. Three repeat readings were taken and the results averaged.

GEOPHYSICAL SURVEYS

Magnetic Fluxgate Gradiometer and Potassium Vapour Surveys

Gradiometer surveys were carried out using the Geonics™ FM36 Fluxgate Gradiometer. The FM36, with 0.5 m vertical sensor separation, measures the vertical component of the local magnetic field. Survey line separations were 0.5 m with reading intervals of 0.25 m or 0.5 m along the lines (Table 1). A parallel traverse method was adopted in a south to north orientation and readings were acquired at ~0.3 m above the ground. The winter surveys had the magnetometer calibrated every half hour to reduce the effect of thermal drift. Surveys were also repeated three times consecutively at each site. All surveys comprised 'single' surveys post burial except for the Keele University site, which was subject to repeated (time-lapse) data collection at monthly intervals over a period of three months. The Lincoln survey (see Table 1 for survey summary) was carried out using the potassium-vapour GEM™ (GSMP-40) instrument with 1 m vertical sensor separation. The GSMP-40 has the additional advantage of not needing calibration Both the FM36 and the GSMP-40 are very sensitive (0.01 and 0.001 nT respectively) and are suitable for resolving to the required penetration depths (~0.5 m).

Magnetics Data Processing and Analysis

The magnetic survey data has been subject to minimal processing, to preserve original and subtle anomalies, using ArcheoSurveyor 2 software. The median filters were

applied to remove any high frequency noise. All data was then normalised in order to allow quantitative comparisons. Subsequent standard deviation (SD) histograms were produced displaying variance over the anomalies and/or grave sites (see Table 2).

Bulk Ground Resistivity Surveys

Bulk ground resistivity surveys were acquired at all sites (using a twin-array, custom built frame, in a dipole-dipole configuration with 0.1 m long electrodes at a constant 0.5 m spacing see Jervis *et al*. 2009a; Jervis *et al*. 2009b). The survey lines had a 0.5 m separation and a 0.25 m reading interval unless otherwise stated (Table 1). The remote probes were placed ~17 m from the survey area with a separation of 1 m apart following standard methodologies (see Milsom, 2007). The survey was carried out using a parallel traverse in a south to north orientation. The equipment, although occasionally can be susceptible to thermal drift, did not require calibration.

Bulk Ground Resistivity Processing and Analysis

All resistivity data was processed using the GMT and ArcheoSurveyor software (Wessel & Smith, 1998). The raw data was gridded and third order polynomial trends were removed. For further details see Table 2 and Jervis *et al.* (2009a,b) for details.

RESULTS

The processed Keele University (semi rural environment) data displayed variable magnetic gradients (-1.3 to +1.2 nT; Fig. 5). Strong dipolar magnetic-gradient anomalies were contained within all the data sets but varied spatially between them. They were generally located at the edges of the survey area. Resistivity results showed low resistivity over the 'naked' pig, whereas, there was a clear high resistivity anomaly over the 'wrapped' pig (Fig. 5d). The ICP-OES chemical analysis of the pig leachate samples over the one year survey period showed an overall increase in ions over time, after the background control lysimeter values had been subtracted (Fig. 6a). This is particularly evident for the Potassium (0 to 69 ppm), Magnesium 0.2 to 3.7 ppm), Sodium (0 to 29.7 ppm), Calcium (0.1 to 38.2 ppm) and Iron (0- 8 ppm). Following the conversion of post-burial days to Accumulated Degree Days (ADD), by weighting each day by its average daily temperature (see Vaas *et al.* 1992 methodology), the somewhat irregular temporal increases in concentration appear more linear (Fig. 6b). Conversion of days to temperatures is most important as it overcomes site-specific seasonal temperature changes and is the most important variable to quantify as it directly relates to decomposition rates (see Vass et al. 1992; Carter & Tibbett, 2009).

The Staffordshire University Crime Scene House (urban environment) magnetic data displayed moderate to low gradient anomalies in close proximity to the simulated grave (~0.07 nT; Fig. 7). A strong dipolar anomaly was visible to the west of the

grave site (+0.16 nT). In comparison moderate resistivity values were recorded over the simulated grave site (0.62 Ω.m).

The processed Lincoln University (woodland environment) potassium vapour data contained a number of dipolar anomalies along the west margin of the survey area (+120 to -100 nT respectively). There was an anomaly of elevated gradient situated over the largest of the buried cadavers (~20 nT). However, there was little magnetic variation over the small buried cadavers (~0 nT). The resistivity data, however, displayed high anomalies over all the simulated graves and along the northern margin of the survey area (~3 Ω.m). Resistivity anomalies were also present over the surface cadaver positions. Simple Mag2DC forward modelling of the anomaly over the 'shallow' cadaver showed a ~0.5 m x 1.0 m body at a depth of less than 0.2 m (Fig. 8). Unlike the other sites where only gradient data was obtained, the Lincoln University total magnetic fields data also provided the ability to create simple 2D models using Mag2Dc v.2.10 freeware. A near-surface model of magnetic targets and their magnetic susceptibility contrast with background values was created so that the modelled magnetic data would best-fit (1.24% misfit) the observed magnetic data (Fig. 8c).

The Abbey Hulton (control urban environment) magnetics data contain several potential targets (nT; Fig. 9). To the east there was a very high gradient bulls-eye that also had dipolar characteristics (1nT +). Comparative resistivity data contained high resistivities orientated North-South on the western margin of the survey area and

trending East-West through the survey centre (+0.65 to 1 Ω.m). Very low resistivities were visualised along the southern margin of the survey area (~0.2 Ω.m).

Additional dataset analysis was carried out in order to try and quantify the magnetic anomalies. SD histograms were produced for subsets of the magnetic surveys (3 m x 3 m grids). The variance was calculated in SD for each line of the subset over the potential and known grave sites (e.g. Fig. 5a). The skew of the subset histogram was compared to that of background readings. The anomalies/grave sites displayed slightly negative skews whereas the background displays normal distributions.

DISCUSSION

The use of magnetics in criminal investigations has previously yielded positive results, especially when employed in a multi-technique study (Nobes, 1999). The technique has had even more success when locating ancient burials as demonstrated by Linford (2004). Although magnetic anomalies found by other authors have provided good indicators for follow up investigations, the results are non-unique and neglect site and target specific controls on the geophysical responses. Furthermore, there have been not been previous simulated studies that assess the effectiveness of the technique from an archaeological-forensic point of view or that compare the results with other widely used methods, such as bulk ground resistivity. Creating a range of simulated burials using similar target types within contrasting environments has allowed for the

comparison of both the magnetic and electrical resistivity responses to be characterised. Moreover, the quantitative comparison between ground conditions and the geophysical response was particularly important in heterogeneous environments such as made-ground or built-up urban areas where magnetic 'noise' can diminish the more subtle magnetic responses.

The Keele University (semi-rural environment) magnetic data set contained a number of high gradient bulls-eye anomalies that were probably a result of either processing or the presence of significant metallic debris that may have been present (Fig. 5a/b). However, there was an overall trend of decreasing magnetic gradient with time (Fig. 5c). This contradicts the analytical ICP-OES data which displays an overall increase in iron within the grave decomposition fluids with time (Fig. 6). The Crime Scene House (urban environment) magnetic data set displayed no large anomalies over the position of the grave (Fig. 7). Slightly elevated gradients (0.04-0.11nT) over the grave could indicate disturbed ground. A high gradient, dipolar anomaly was situated to the west of the survey indicating the presence of a metallic object. Low gradient anomalies were in close proximity to large trees and the car park area, although both were lacking surface metallic debris and obviously disturbed ground. The Lincoln University (woodland environment) magnetic data set was marginally more successful, yielding subtle anomalies over shallow buried cadavers (Fig. 8). The majority of the survey displayed very low gradients close to 0 nT with high dipolar anomalies at the edge of the survey potentially related to edging effects or metallic debris. Interestingly, the elevated gradient located over the surface pig graves could be related to soil disturbance and/or enhanced susceptibility from bacterial action (Fig.

8b). These positions were confirmed using the simple 2D forward modelling (Fig. 8c). Further entomological analysis would be required to confirm this. There were no anomalies related to the more deeply buried pig cadavers. The Abbey Hulton (urban control) magnetic data set contained linear trends and high gradient bulls-eye anomalies consistent with disturbed made-ground and processing artefacts (Fig. 9). However, when compared to a site plan (Fig. 9c) the highest bulls-eyes coincided with the location of a lead melting hearth and smaller related fires. If the magnetic anomaly were indeed caused by a discreet object such as a hearth, then the stone and soil would retain a sufficiently high enough magnetic thermoremnance to produce such a response.

The magnetic surveys have therefore produced mixed results (Figs. 5, 7-9), with the best results seen in semi-rural environments. The poor magnetic delineation of graves was probably due to the high ferrous metal content of the soil and/or made-ground materials; this is particularly evident in urban environments. A lack of magnetic delineation was suggested to be due to the presence of a non-magnetically susceptible material (the wrapped cadaver) and/or an insufficient magnetic contrast with the surrounding soil background values. From the simulated data sets, there appears to be a decreasing magnetic response with time since burial, although there were strong magnetic anomalies present in the control data set. This was suggested to therefore be due to the disturbed ground rather than associated with the grave contents themselves. Collecting total field magnetic data (such as the Lincoln woodland test site) did allow forward modelling to be undertaken to determine the likely depth of the target below ground level. This information would be very useful for forensic search investigators.

Comparative bulk ground resistivity surveys were conducted over the same sites. Published studies of both case and simulated studies regarding the use of resistivity in shallow surveys demonstrated the effectiveness of the technique (Buck, 2003; Scott & Hunter, 2004). This is supported by the results produced in this study whereby the resistivity was able to locate all the simulated graves (Fig. 5c, 7c, 8d). However, the Medieval graves at Abbey Hulton (urban environment) control test site were not located; this was interpreted to be due to their age (~500 years) and the significant disturbed ground that they were located in.

Low resistivity anomalies, with respect to background values, were situated over empty graves and unwrapped cadavers at the Keele University (semi-rural), Staffordshire University (urban) and Lincoln University (woodland) test site suggesting an increase in grave fluid conductivity from either the cadaver grave 'fluid' and / or ground-water (Figs. 5d, 7d and 8d respectively). However, high resistivity anomalies over wrapped cadavers at the Keele test site (Fig. 5d) strongly suggest the containment of grave 'fluid' by the plastic sheeting, reduced inflow of groundwater and the presence of tarpaulin conductive material (Jervis *et al.* 2009b). Interestingly the surface burial positions at the Lincoln (woodland environment) test site were also successfully located by resistive low anomalies with respect to background values, even though no surface tissue remained (Fig. 8d). It is theorised that this was due to conductive decomposition fluids being retained in the soil directly beneath a body. This has important implications for locating primary deposition sites

if a body was moved, or to locate the final position even when no surface physical evidence is present.

CONCLUSIONS

This research details three forensic geophysical studies over shallow buried, simulated, clandestine burials within contrasting environments and one study over a control grave site. This is the first published paper to compare magnetic and electrical resistivity methods, assess the results to specific depositional environments, undertake repeat magnetic surveys and chemically analyse grave 'fluid' for major element changes over time. The potassium vapour magnetometer was deemed the most successful magnetic technique. However, it is difficult to conclude whether the magnetic anomalies over the graves were due to increased magnetic material due to biological activity or from the disturbed ground. To investigate this further, the repeat magnetic surveys would need to be carried out over a longer time period. Interestingly the surface burials at Lincoln were able to be geophysically located by both magnetics and resistivity, even with no surface evidence remaining. The resistivity surveys were more successful as they not only defined the locations of the gravesites from burial, but they also showed some development of the grave area in the semi-rural study, probably grave 'fluid' conductivity. However, resistivity surveys were unsuccessful at locating the control graves.

This study illustrates the importance of using a combination of geophysical techniques. Not only can the nature of resulting anomalies be compared, but a relatively large area can be covered in a short amount of time. From this study it can be concluded that magnetics can be relatively successful when locating clandestine graves. However, this technique was inconsistent and it is more effective for locating older burials. For optimal use of magnetic techniques in forensic investigations, it is suggested that they are used in areas of low electromagnetic noise, such as open rural or semi-rural sites with little or no metallic content in the soil. Likewise, bulk ground resistivity is insufficient as an independent forensic-geophysical tool for locating clandestine burials. However, in comparison to the magnetic techniques it was more successful, providing a greater number of potential targets. Follow-up GPR surveys over identified anomalous areas are suggested for forensic search investigators.

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FIGURE CAPTIONS:
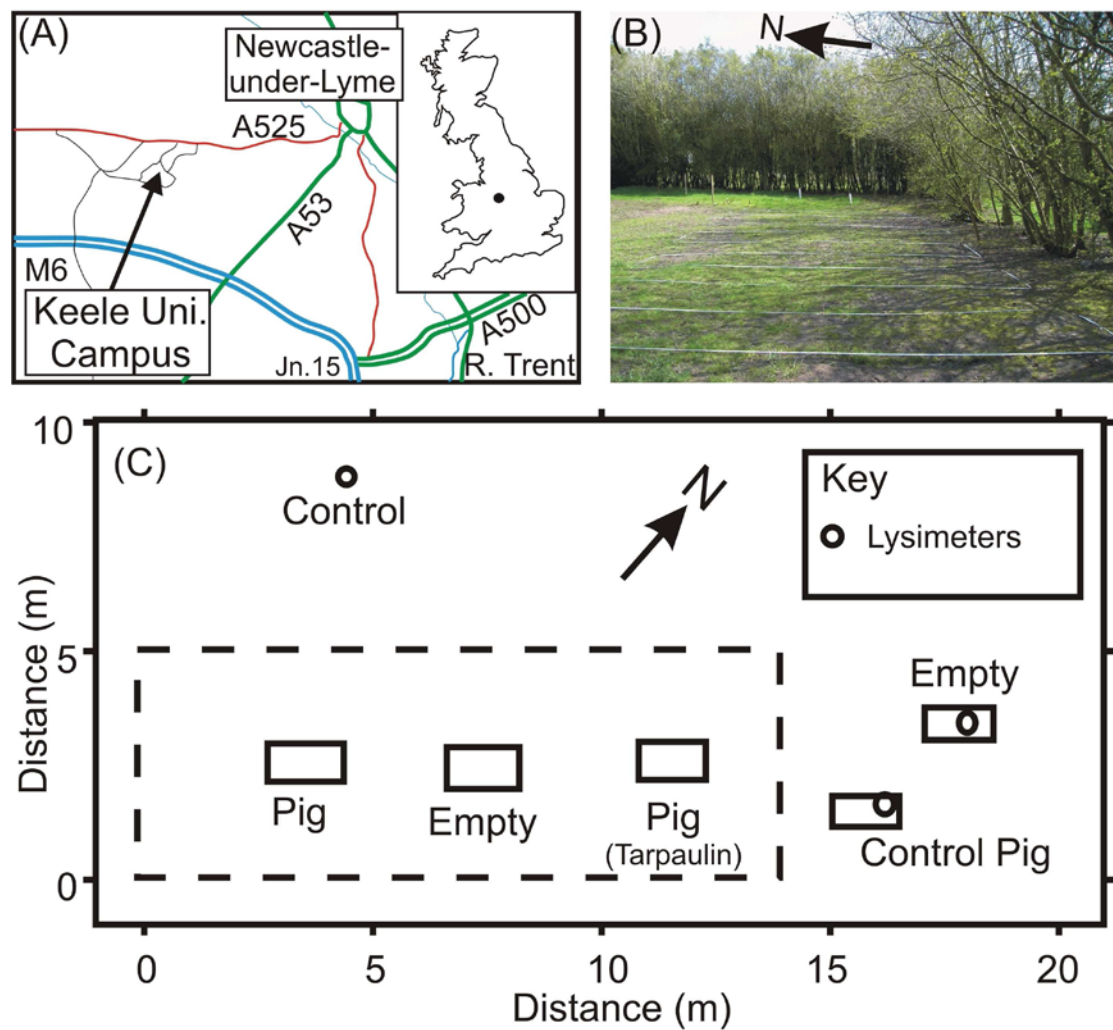
<u>FIGURE 1</u>. Keele University (semi-rural) study site. (a) Location of the study site; (b) photograph of survey area facing northeast; (c) plan of the survey area, displaying the grave locations (adapted from Jervis *et al.* 2009b).
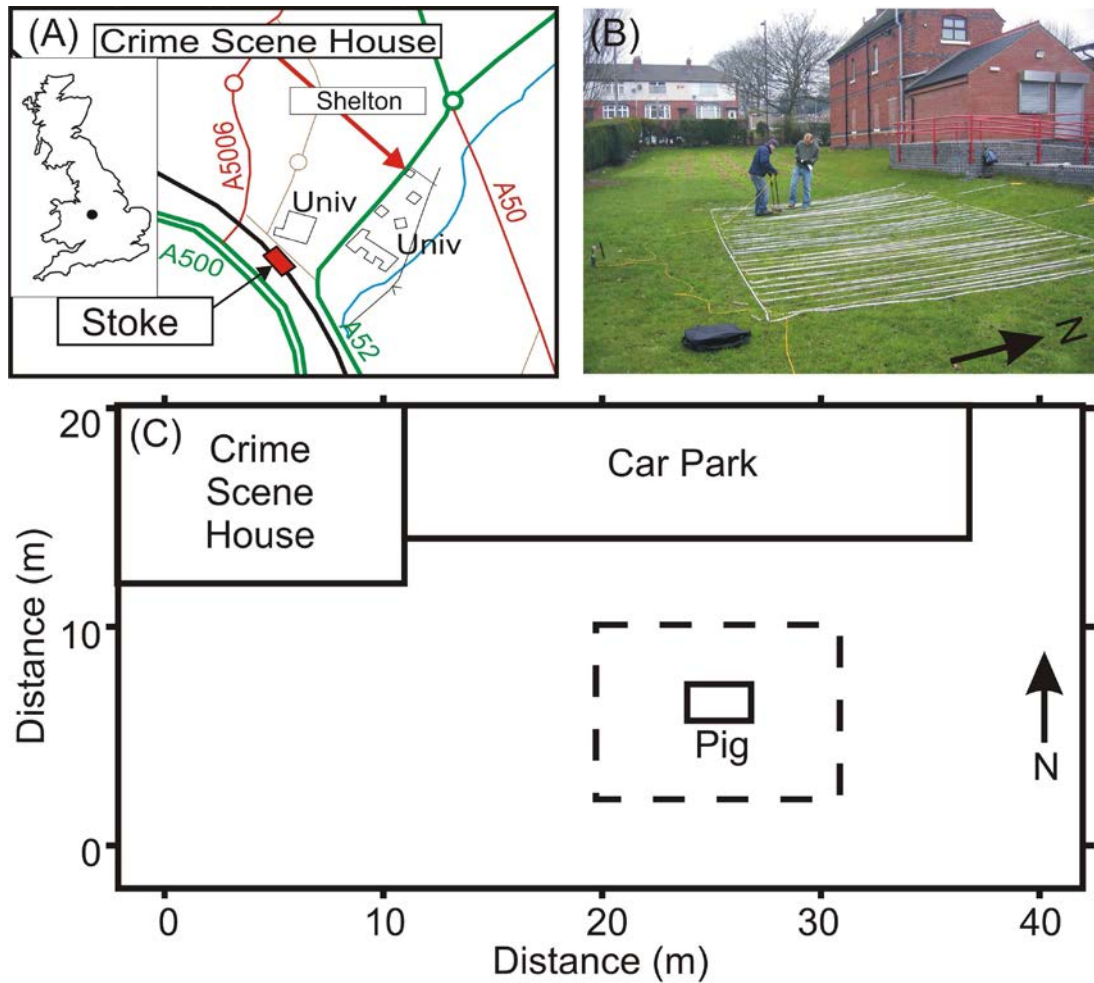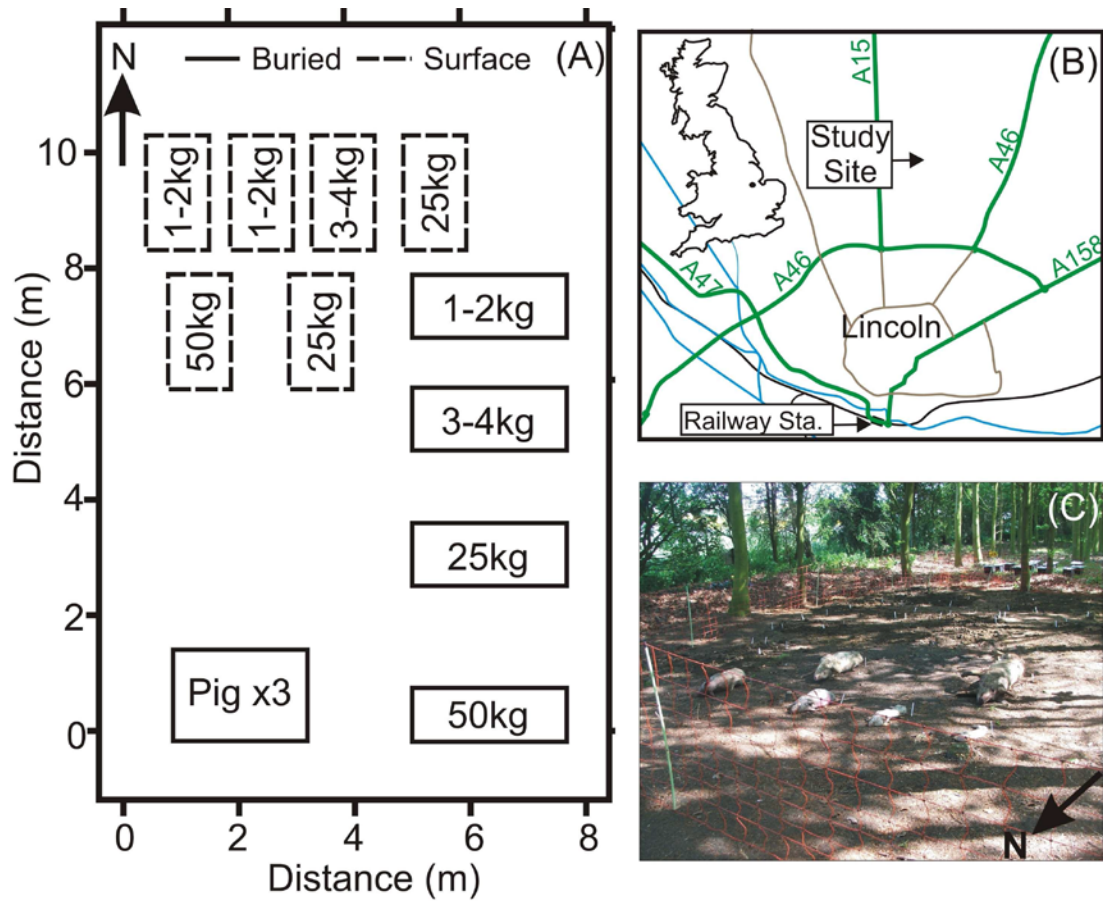
FIGURE 2. North Staffordshire University (urban) study site. (a) Location of the study site; (b) photograph of survey area facing northeast; (c) plan of the survey area, displaying the grave locations (adapted from Jervis *et al.* 2009a).

FIGURE 3. Lincoln University (woodland) study site. (a) Location of the study site; (b) photograph of survey area facing northeast (white markers indicating grave positions); (c) plan of the survey area, displaying the grave locations and cadaver weights.
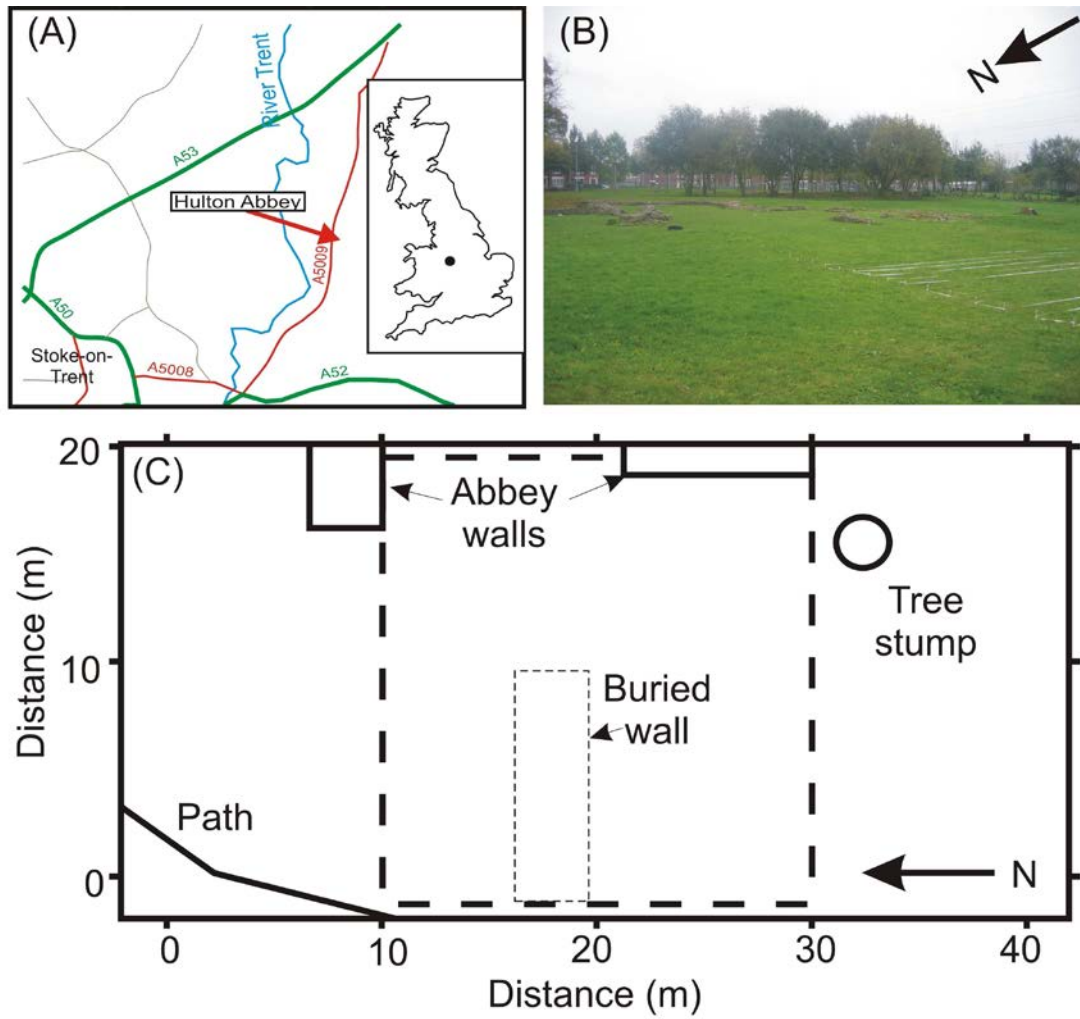
FIGURE.4. Abbey Hulton (control) study site. (a) Location of the study site; (b) photograph of survey area facing northeast; (c) plan of the survey area, displaying the pertinent features.
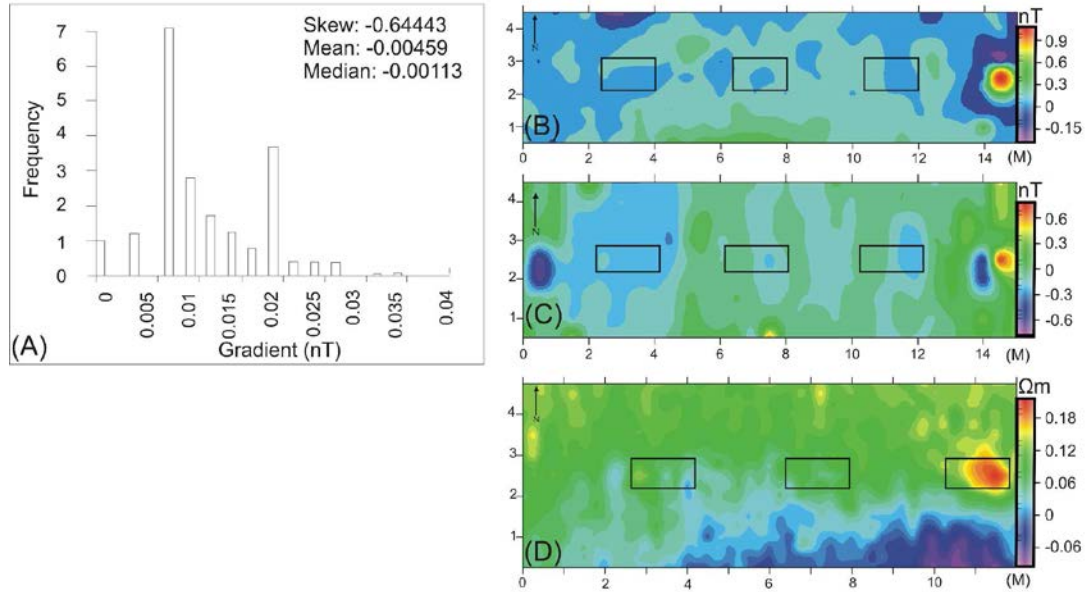
FIGURE 5. Map view of Keele fluxgate gradiometer processed data. (a) SD histogram; (b) 1 month post-burial (7.1.2008); (c) 'difference' magnetic gradient map displaying contrast between immediate and 3 month post-burial survey. (d) Comparative bulk ground resistivity data set. All grid scales in metres. Black squares indicate positions of (left to right): naked pig, empty grave and wrapped pig cadaver respectively (see Fig. 1).
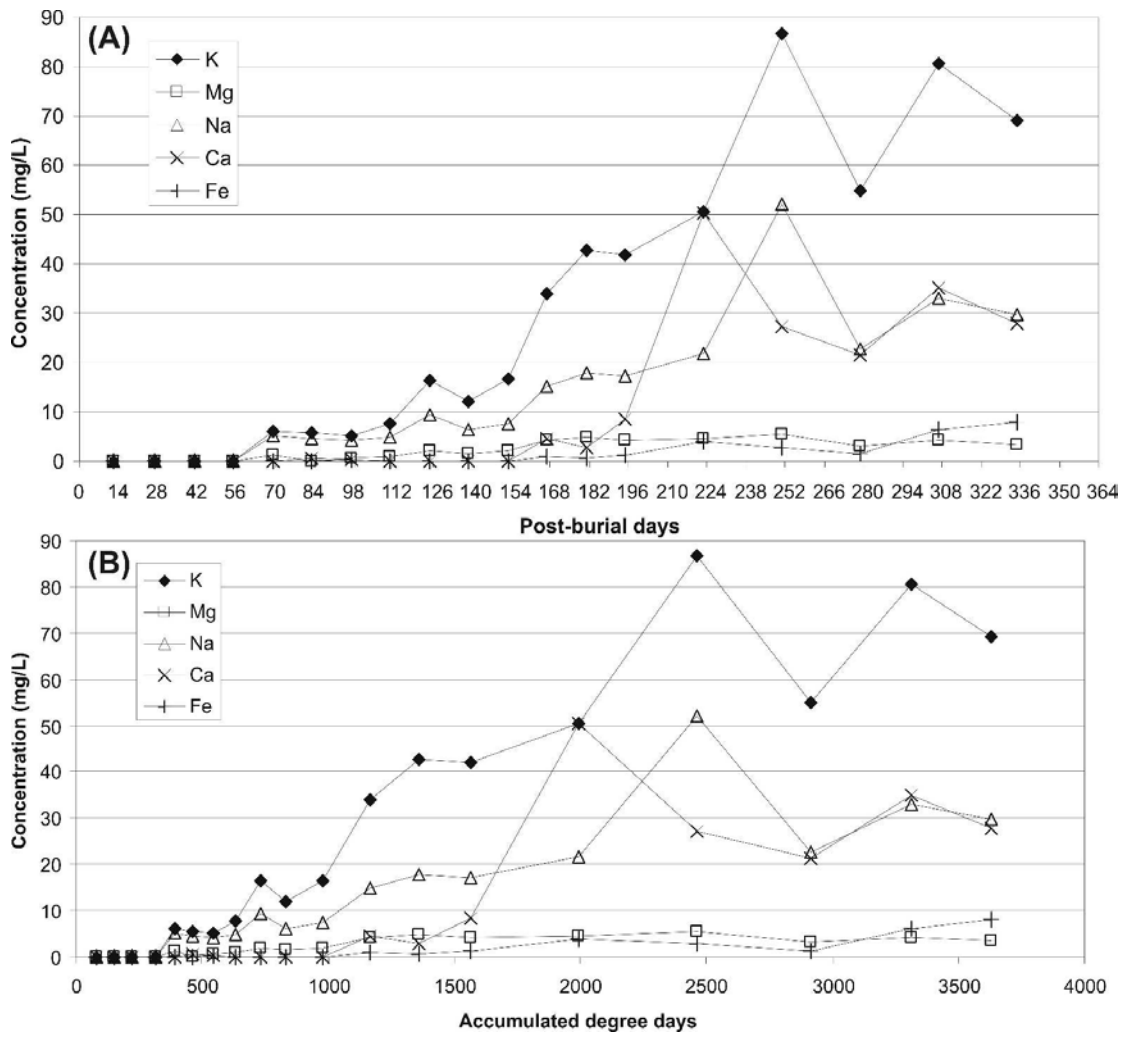
FIGURE 6. Pig leachate fluid laboratory ICP-OES analytical measurements of selected element concentrations. Background (control) values have been subtracted from pig leachate values. Graphs shows results plotted against (a) post-burial days and (b) accumulated degree days respectively (see text).
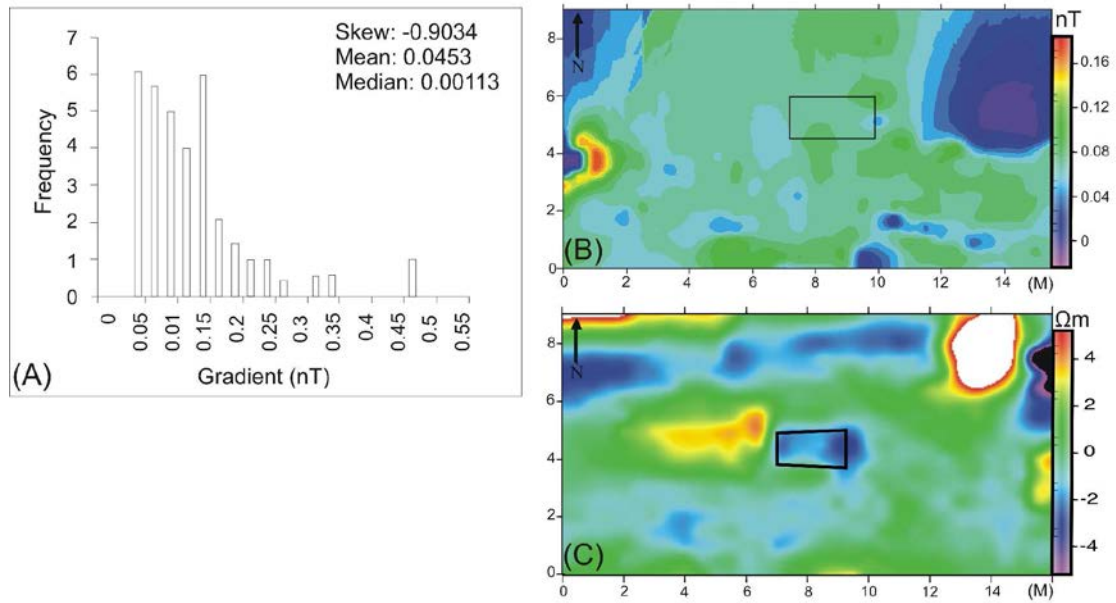
FIGURE 7. Map-view of Staffordshire University fluxgate gradiometer processed data. (a) SD histogram; (b) 3 months post-burial (15.6.2007); (c) comparative bulk ground resistivity data set. Black square indicates position of pig cadaver (see Fig. 2).
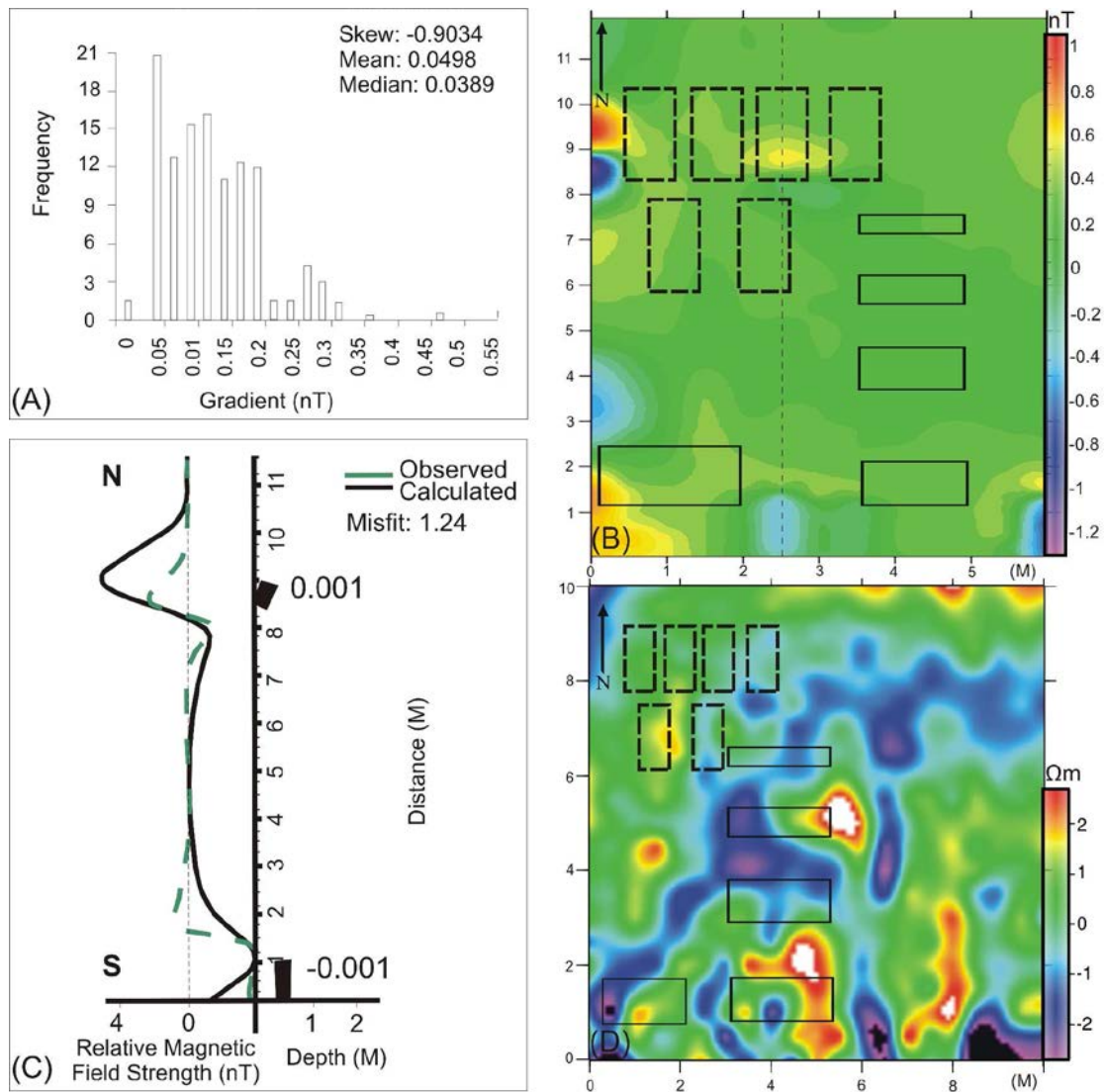
FIGURE 8. Map-view of Lincoln University fluxgate gradiometer processed data. (a) SD histogram; (b) 7 months post-burial (11.11.2007); (c) Mag2Dc 2D forward model of the total field over line 2.5 m (see (b) for location). Solid black squares indicate graves positions, dotted squares indicate surface burials (see Fig. 3); (d) comparative bulk ground resistivity data set.
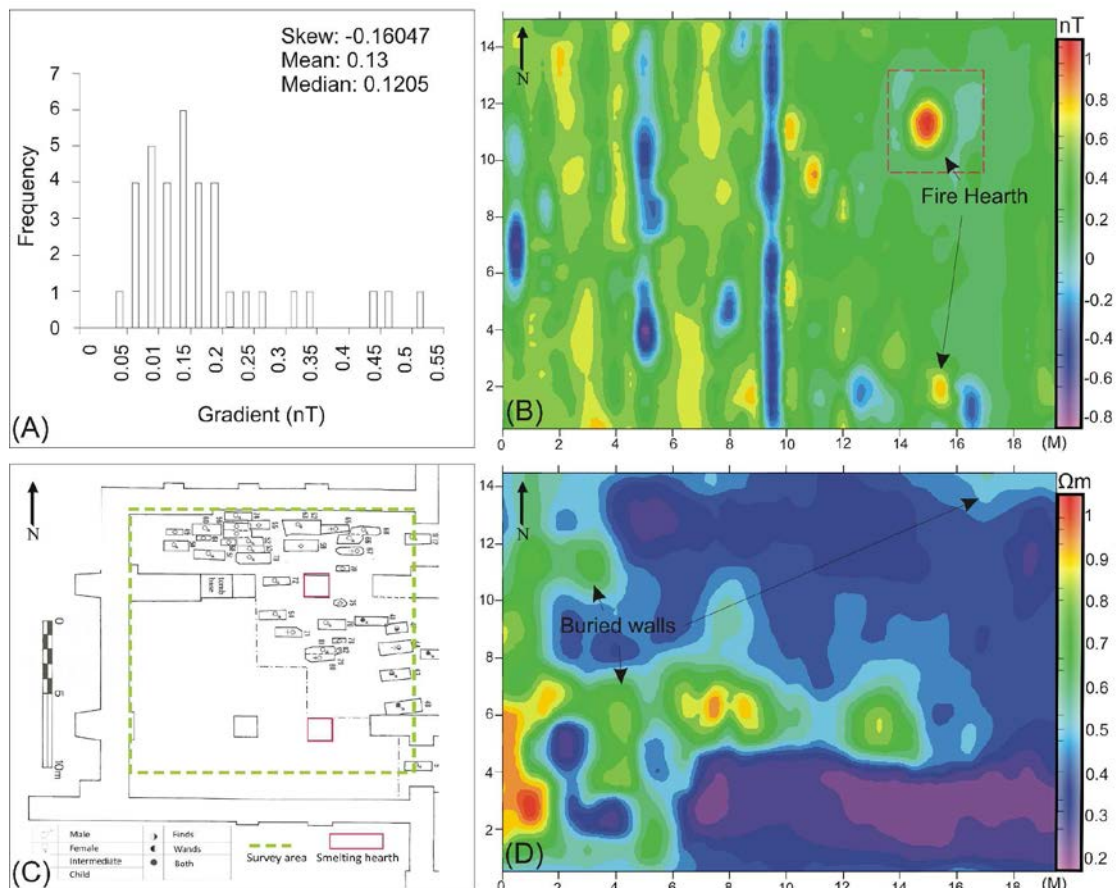
FIGURE 9. Map view of Abbey Hulton fluxgate gradiometer processed data (a) SD histogram; (b) fluxgate gradiometer survey (1.11.2007); (c) discovered below-ground Abbey remains and excavated graves with marked survey area (modified from Boothroyd & Klemperer 2004); (d) comparative bulk ground resistivity data set.

TABLE CAPTIONS:

	Keele University, Staffordshire, UK	Staffordshire University, Staffordshire, UK	Lincoln University, Lincolnshire, UK	Abbey Hulton, Staffordshire, UK
Depositional Environment	Rural	Urban	Woodland	Urban
Soil Type	Sandy loam with clay horizons	Made ground, fluvial sand & gravel	Sandy loam	Made ground, sandy loam
Av. soil moisture content (%)#	27%	25%	Not measured	27%
Average soil magnetic susceptibility values (S.I.)$	16 x 10^{-5} (400)	126 x 10^{-5} (459)	Not measured	Not measured
Bedrock Type	Carboniferous Butterton Sandstone Formation.	Carboniferous Coal Measures	Jurassic Lincolnshire Limestone Formation	Carboniferous Coal Measures
Target	Pig cadavers	Pig cadaver	Pig cadavers	Monk graves
Known target location	Known	Known	Known	Unknown
Target number	3	1	11	Unknown
Target Size (areally)	~1 m x 0.5 m	~1 m x 0.5 m	~1 m x 2.5 m ~6 m x 7.4 m	~2 m x 1.5 m
Depth (bgl)*	~0.5 m	~0.5 m	surface & ~0.6 m	~2 m
Target covering	1 x naked and 1 x wrapped	Naked	Naked	Unknown
Survey grid size	5 m x 15 m	4.5 m x 8 m	8 m x 11 m	20 m x 20 m
Sample interval	0.25 m on 0.5 m lines	0.25 m x 0.25 m	0.25 m x 0.25 m	0.25 m x 0.25 m
Geophysical Survey type	Fluxgate gradiometry & electrical resistivity	Potassium vapour gradiometry & electrical resistivity	Fluxgate gradiometry & electrical resistivity	Fluxgate gradiometry & electrical resistivity
Burial date	07.12.2007	15.03.2007	28.04.2007	500+ years
Survey date	07.01.2008 & 28.02.2008	07.06.2007	11.11.2007	05.12.2007
Post-burial days	31 & 83	84	197	Unknown
Accumulated degree days	175 & 461	891	2800 estimated	Unknown

(ADD)[+]	

TABLE 1. Summary of magnetic study sites, survey specifics and timings. *Bgl signifies below ground level. [#]Average soil moisture content values taken from Jervis *et al.* (2009a,b) and a 2008 student project for the Abbey Hulton site. [$]Numbers in brackets indicate total measurements taken. Keele University data taken from Dale (2006) and Staffordshire University data taken from Pringle et al. (2008). [+]ADD days

Data Processing Steps	
1	Digital data transferred to Microsoft Excel and converted to x,y,z value column format
2	Median filtering of whole survey datasets
3	Normalise whole survey dataset
4	Data interpolation in Golden™ Surfer Software using a minimum-curvature or kriging surface algorithm
5	Low pass Gaussian filter applied to remove high frequency noise
6	Removal of linear site trends
7	Data plotted using a rainbow colour scale to produce gradient maps or total field (for the Lincoln data set)
8	A subset over the grave was selected and returned to raw data (x,y,z) format
9	Standard deviation histograms plotted for the data subset
10	Steps 1-8 repeated for potassium vapour magnetometer before basic forward modelling using Mag2Dc for Line 2.5 from Lincoln study site.

calculated from Keele meteorological station temperature probe at 0.5 m bgl (see text).

TABLE 2. Fluxgate gradiometry and potassium vapour magnetometry data

processing steps. Methodology adapted from Pringle *et al.* (2008).