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TIME-LAPSE NEAR-SURFACE GEOPHYSICAL MONITORING OVER SIMULATED CLANDESTINE BURIALS OF MURDER VICTIMS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF GRAPHS

LIST OF TABLES

ABSTRACT

This thesis is involved in a long-term monitoring project carried out at Keele University (Staffordshire, UK): the aim is to improve the current understanding of the detection of clandestine graves of murder victims with geophysical electric resistivity surveys and to provide forensic search teams of the NPIA (U.K. National Police Improvement Agency) with systematic geophysical monitoring data over simulated burials for comparison to active cases. Resistivity surveys were conducted over a test site in two controlled experiments: Constant Offset Resistivity and Electrical Resistivity Imaging. In both experiments, grave containing pig cadaver is initially associated with low resistivity anomaly, indicating it is primarily caused by increased soil-water conductivity which is suggested to be caused by decomposition fluid from the buried cadaver. The anomaly is then observed to vary, becoming progressively undetectable and later an increasing high resistivity anomaly appears: the decomposition fluids are widespread into the surrounding soil while the skeleton, which is highly conductive with respect to the background values, is detected as a high resistance anomaly. The non-detection of an 'empty grave', containing only disturbed soil suggests that disturbed soil do not contribute to the grave-related anomaly. In the same experiment, it was found that wrapping a cadaver prior to burial can influence a grave's resistivity response, as a grave containing a cadaver wrapped in tarpaulin is generally associated with a high resistivity anomaly. This is suggested to be because the tarpaulin restricted the release of decomposition fluid in the soil and the wrapped cadaver subsequently impeded the flow of electrical current in the ground.

Further analysis on data statistics indicated that the resistivity responses were influenced by environmental influences: the variability of the soil moisture budget and the existing tree root system can diminish the detectability of the target.

Resistivity surveys are able to detect the simulated graves with variable effectiveness over time post burial and the tested methods provide a complementary information about the subsurface. It is then fundamental to be aware of the type and magnitude of the anomaly to be expected.

L'attività di ricerca presentata in questa tesi è coinvolta in un progetto di monitoraggio a lungo termine svolto presso Keele University (Staffordshire, UK) che mira a migliorare l' attuale comprensione nell'individuazione di sepolture clandestine di vittime di omicidio tramite indagini geofisiche di resistività elettrica e di fornire alle squadre di ricerca di medicina legale del NPIA (U.K. National Police Improvement Agency) dati di un monitoraggio geofisico sistematico per il confronto con casi applicativi. Indagini geofisiche di resistività sono state condotte su un sito di prova con sepolture simulate adottando due tipologie di esperimenti: resistività ad offset costante e Imaging di resistività elettrica. In entrambi gli esperimenti, la sepoltura simulata è inizialmente associata ad un'anomalia di bassa resistività, indicando che è principalmente causata da un aumento della conduttività dell'acqua freatica causato dal liquido di decomposizione del cadavere sepolto. L'anomalia viene poi osservata variare, diventando progressivamente non rilevabile e successivamente appare come un'anomalia ad alta resistività: i fluidi di decomposizione sono diffusi nel terreno circostante mentre lo scheletro, che è altamente conduttivo rispetto ai valori di fondo, viene rilevato come un'anomalia ad elevata resistività. La mancata individuazione della sepoltura vuota, contenente il solo terreno disturbato, suggerisce che esso non contribuisca all'anomalia in corrispondenza della sepoltura. Nello stesso esperimento si è constatato che avvolgere un cadavere prima della sepoltura può influenzare risposta in resistività: la sepoltura contenente il cadavere avvolto in un telo è associata ad un'anomalia ad elevata resistività. Il telone limita il rilascio del fluido di decomposizione nel suolo ed impedisce il flusso di corrente elettrica nel terreno.

Ulteriori analisi sulle statistiche dei dati hanno indicato che i responsi sono influenzati da fattori ambientali legati al contesto: la variabilità del bilancio di umidità del terreno e l'apparato radicale esistente possono diminuire la rilevabilità del bersaglio.

Le indagini geofisiche di resistività sono in grado di rilevare le sepolture simulate con efficacia variabile nel tempo trascorso dalla sepoltura ed i metodi testati forniscono un'informazione complementare sul sottosuolo. E' quindi fondamentale essere consapevoli del tipo e dell'entità dell'anomalia attesa in base al target ricercato.

INTRODUCTION

This thesis is the result of my experience at Keele University (UK), collaborating with local geophysics researchers and students.

The study was undertaken within a geophysical long-monitoring project over a controlled test site at Keele University campus. I was enrolled to assist the Forensic Geophysics researcher Jamie K. Pringle in the field work at the beginning of the sixth year of monitoring activity over simulated clandestine burials. The hosting Keele University provided all necessary administrative and logistical support, dedicated laboratory desk space, access to geophysical and survey equipment and relevant software and project supervision.

After training with Geoscience students I was given the opportunity to carry out GPR (Ground Penetrating Radar with four different antennae frequencies) and Electrical Resistivity data collection by myself and I was given free access to the data of the previous years of activity and to the processing techniques adopted. In agreement with Dr. Jamie K. Pringle the planned activities had been the following:

- *collect geophysical datasets over simulated clandestine burials*
- *process and interpret said datasets*
- *integrate with previously collected datasets*

Moreover I was invited to take part to many field activities conducted by the School of Physical and Geographical Sciences such as a one-week geophysical field work in the Lake District area and a two-days geological trip in Wales. I also participated to conferences and discussions about Forensic Geophysics.

This academic work is structured in an initial contextualization and the state of the art about Forensic Geoscience and Geophysics; then the case study is presented and the applied geophysical methods are introduced. Data processing steps are fully explained and final results showed and discussed.

CHAPTER 1

CONTEXT: FORENSIC GEOSCIENCE & GEOPHYSICS

1.1 FORENSIC GEOSCIENCE OR GEOFORENSICS

1.1.1 Definition, History and Purposes

Pye and Croft (1) define Forensic Geoscience as “the application of geoscience and wider environmental science techniques to investigations that could potentially be brought before a court of law”.

As such, it encompasses a number of sub-disciplines, such as forensic geology, forensic geophysics, forensic soil science, environmental forensics, forensic mapping, geomatics and remote sensing. There is also a significant overlap with related disciplines, such as forensic archaeology, forensic engineering and forensic botany.

Geoscientific methods are applied to search for objects or substances that are concealed in the ground and whose presence there constitutes some form of civil, criminal or humanitarian crime.

The forensic objects being searched for could be:

- illegally buried weapons,
- explosives and landmines,
- drugs,
- clandestine graves of murder victims,
- mass genocide graves,
- toxic wastes in illegal.

Forensic geoscience is currently considered not only to be an emerging discipline that can bring significant benefits to policing, but an application of geoscience methods that can provide important results in environmental, humanitarian, military and engineering investigations (7).

The traditional use of soil or sediment analysis was expanded in the 1990s when geoscience methods started to become applied for forensic searches for buried or concealed objects, largely because of the widespread use of remotely-sensed data and increasing ease of use and good quality outputs from shallow geophysical methods.

Since the turn of the millennium, there has been an increased use of forensic geoscience methods in law enforcement, environmental and humanitarian search investigations which have correspondingly led to an increased number of published articles. Within the last ten years a rapid expansion of this area has taken place.

1.1.2 Locating clandestine graves and law enforcement

This work concerns the search of clandestine graves related to criminal investigations. As stated before, geoforensic methods can act like law enforcement tools.

There are four core functions that can describe all law enforcement activity:

- investigation,
- interview,
- search,
- recovery.

It is the 'search to locate' aspect of law enforcement that presents the greatest challenge. Without locating the evidence, or the victim's body, rarely will a conviction succeed and justice be served however satisfactory the investigation has been conducted, and even if a confession has been obtained from the suspect (10).

A UK law enforcement definition of 'search' is "the application and management of systematic procedures and appropriate detection equipment to locate specific targets" (3). Search work involves the elimination of suspected locations as much as finding the remains in question. Not finding buried remains is not a measure of failure, but a reminder that a forensic search is as much about negative evidence and elimination as it is of discovery.

Moreover, individual human burial constitute a relatively small portion of the homicide total (approximately 9% in the UK), but locating them occupies a disproportionate effort in terms of manpower, general deployment of resources and operational time. Extended searching for victims also generates unwelcome publicity and can place pressure on law enforcement authorities (8).

Forensic geoscience information may be used simply for intelligence purposes within the frame-work of an ongoing police investigation or as evidence for presentation in court, depending on the quality of data and strength of the conclusions which can be drawn.

The design and phased implementation of a search strategy for a homicide grave includes (10):

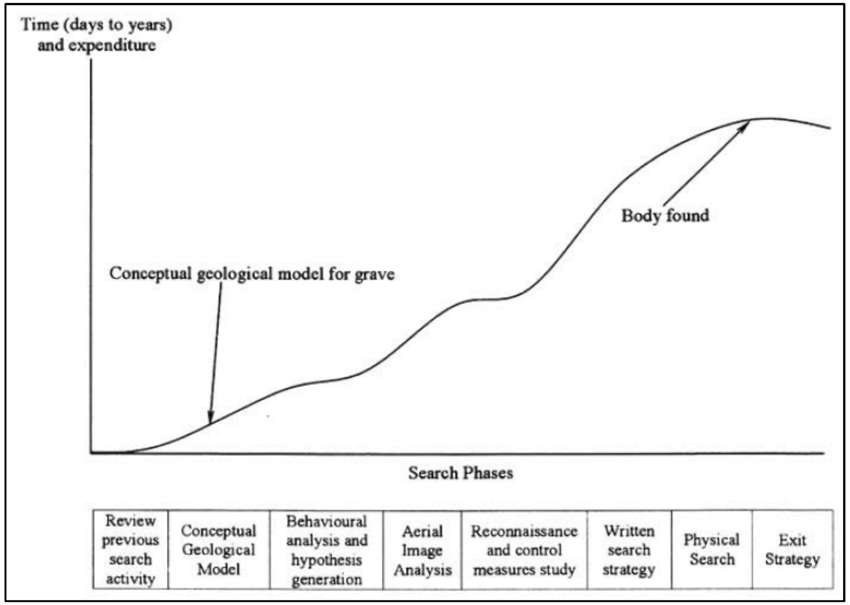

Fig 1.1: schematic diagram showing the phases and time/expenditure in a search to locate a homicide victim. The duration, axis values and morphology of the curve will vary for each search (10)

Desk study: All available intelligence, geological and other information concerning the site is reviewed, collocated and analyzed to identify the limits of the search area/areas. It includes the examination of background information provided by the following geoscientific methods:

- Remote sensing,
- Geomorphology,
- Geology and soil mapping,
- Metal detectors,
- Search dogs.

Development of a conceptual geological model: produce a model to identify likely ground conditions, geology and general characteristics of the site.
An understanding of the undisturbed (pre-burial) and disturbed (post-burial) geology and the target (body and associated objects) properties are crucial before the correct search strategy and choice of instrumentation may be decided, and the optimum method of deployment identified.

Behavioral analysis (offender profiling) and hypotheses generation: this phase results in the development of the likely search scenario hypotheses and predictions of the expected place of concealment and condition of the victim.

Aerial image analysis: current and historical aerial and satellite imagery, preferably before the victim's disappearance, for identifying location consistent with the suspect's behavioral profile parameters and identify ground disturbances and suitable conditions for the choice of the grave location.

Reconnaissance site visits: A detailed 'walk over' survey to obtain an appreciation of the search area and identify technical, logistical or access constraints

Development of a written search strategy: producing a document to support decisions. Include relevant information uncovered in the desk study, a likely scenario of disposal, informed by behavioral analysis, and the most appropriated way to search the target area based on the field reconnaissance.

Search, review and continue: conducted under the supervision of a law enforcement officer.

Development of a search exit strategy: a written report detailing all the searches actioned, including any associated mapping and documentation of any objects found. Conclude that all investigative facts and intelligence are exhausted and recommend cessation of search.

Financial, technical and/or logistical constrains or availability of specialist resource/equipment will be limiting factors which require careful consideration. The search strategist will decide on the most effective way to achieve the minimum standard (resolution) required for a high probability of search success. A balance is required between a minimum acceptable standard and minimal expenditure when conducting a search.

In recent years soil and geological evidence has been increasingly used in investigations and both criminal and civil law trials in the UK and USA, but world-wide its acceptance in the courts varies from country to country. This partly reflects the different legal traditions, the greatly varying degree of sophistication displayed in the investigation and analysis method between different countries (1).

Active cases which deployed geophysical methods exposed a distinct lack of awareness of systematic search techniques within UK police forces: they identified a general unfamiliarity with the underlying principles of various techniques, a misunderstanding of the value and limitations of particular methods and a reluctance to understand the desirability of using complementary techniques (23).

1.2 FORENSIC GEOPHYSICS

1.2.1 Definition and Purposes

Paul Cheetam (6) defines geophysical survey as "the investigation of the Earth by the measurement of its physical properties. Such physical properties are many and varied. Acoustic, electrical, magnetic and electromagnetic are some of the most relevant properties and these are related to a greater or lesser degree to chemical properties."

What the geophysicist is looking for are measurements that, because of their magnitude or form, stand out from the natural variations that is found to exist in any survey area. If such measurements are identified, then these will be anomalies. If the natural variations are extreme then the often subtle contrasts that result from minor sub surface disturbances (including graves) may well be drowned out by this background geophysical 'noise' and may consequently remain undetected.

Moreover anomalies should not be considered to represent any visual images of the feature. In fact geophysics can be used to interfere a presence but this needs to be interpreted by a process of conjecture and the interpretation must subsequently be confirmed.

Geophysical methods have the potential to aid the location of human remains as they can, non-invasively, very rapidly survey extensive areas where a suspected clandestine burial has taken place. These non-invasive surveys minimize evidential contamination and damage. Subsequent targeted anomalies could then be investigated using conventional intrusive methods.

1.2.2 Geophysical techniques and active cases

Each technique creates a different map of sub-surface, that can vary in visual form and content. There is a significant gap in knowledge of the best methods for collection, analysis and interpretation of geophysical data for forensic applications depending on the type of target. It should be noted that as long as there is a geophysical contrast between a 'target' and the background materials, a target can be identified. Although any change in physical properties of the ground caused by a grave might be brought by a wide variety of different causes, and it is important to be aware of these and their potential magnitude in order to assess the applicability of the technique to a particular site.

Ultimately, forensic geophysics has the potential to develop into a standard technique to assist the police service in both the rapid detection and characterization of clandestine shallow burials. The effective deployment of these techniques requires awareness of their advantages and limitations within different environments, an understanding of the potential of complementarity and, often, the transference of civilian skills into a police context.

Although trying to create a standard methodology, every forensic search of the subsurface will be unique, depending on:

- the target size (e.g. child to adult clandestine burials),
- burial depth below ground level (typically the deeper buried the forensic target, the harder it may be to locate),
- style of burial (e.g. for discovered clandestine graves they are commonly wrapped, clothed or naked),
- time since burial,
- background soil type,
- local bedrock (which often affects overlying soil type)

- depositional environment (e.g. urban, rural, woodland, moorland)
- vegetation type (e.g. grasses, woods, urban gardens),
- local climate (e.g. arid to humid),
- water table depth below ground level,

and many other specific variables. Each of these target and background site variables will have a limited to very important effect on optimum search technique and their subsequent target detection success or failure, so it is very difficult to produce specific guidelines for forensic searches for all eventualities.

This is the reason why the deployment of geophysical techniques to investigations has been relatively slow, partly through the costs of research and the diversity of techniques available, and partly through the difficulty in establishing the effects of the decay dynamic of buried human remains over time. Of particular interest is the dynamic of decay and the optimal configuration for different geophysical instruments before, during and after the decay process, as well as its effect on the data.

Recent advances in field equipment and data processing software has meant that some geophysical techniques are now relatively quick to collect and quantitatively analyse to pinpoint suspected locations for further investigation.

Pringle et al. (7) offer the following updated review of geophysical techniques applied to forensic investigations and related active cases. It includes the following techniques:

- Seismology,
- Electromagnetic survey,
- Electrical methods (Resistivity),
- Ground penetrating radar (GPR),
- Magnetometry.

Seismology

On a large scale, seismology has been used in the investigation of international incidents involving explosions and impacts, as the energy released can be detected by seismic networks. Examples include the investigations of the Kursk submarine disaster (Koper et al., 2001), the Lockerbie (Scotland) aeroplane crash (Redmayne and Turbitt, 1990), the Oklahoma City (US) bombing (Holzer et al., 1996) and the Nairobi US Embassy bombing (Koper et al., 2001; Koper, 2003).

Seismology could also potentially be useful for investigating covert underground tests of nuclear weapons (Douglas et al., 1999). Seismo-acoustic methods are showing promise to detect Improvised Explosive Devices (IEDs), mine and Un-exploded Ordnance (UXO) locations (see Xiang and Sabatier, 2003; Donskoy et al., 2005; Sutin et al. 2009).

These methods utilise differences between the elastic, acoustic and reflective properties of buried objects and the surrounding soil. A major advantage of this technique is that it works well for non-magnetic material, e.g. for detection of plastic mines, and can discriminate mines from smaller, metallic non target material. However, the data can take a relatively long time to analyze compared to other techniques, and it is currently difficult to detect deeply buried material.

Multi-channel analysis of surface waves (MASW) is showing forensic potential; for example, Tallavó et al. (2009) detail how this method could detect 2 m below ground level (bgl) buried wooden trestles that supported Canadian railway embankments.

A microseismic approach has been shown by Arosio (2010) to have the potential to be used to locate earthquake survivors trapped under rubble if sensors are placed around the site and cross-correlating seismic sources are used.
Case studies of seismic methods used to characterise contaminated land sites and illegally buried solid waste are given by Cardarelli and Di Filippo (2004) and Grandjean (2006) respectively.

Electromagnetic survey

There has been limited use of Electromagnetic (EM) surveys for law enforcement investigations, which is surprising considering its relatively rapid survey rate and ability to be carried through woodland environments, where other techniques may not be useful.

Frohlich and Lancaster (1986) deployed a Geonics™ EM-31 instrument in Jordan to locate and characterise unmarked burials and tombs, with resulting target(s) contrasts with background levels dependent on the proportion of silt present within the graves.

Nobes (2000) documented the successful search for buried human remains in a wood, initially by utilising an EM survey to identify anomalous areas, with follow-up GPR investigations over these suspected burial areas. Nobes (2000) also suggested that the victim's clothing may have trapped decompositional fluids during dry conditions (see Section 5.3) which were detected by EM methods.

France et al. (1992) also found EM surveys could successfully locate simulated clandestine burials of pig cadavers in the Western US. Larson et al. (2011) suggested low-energy EM fields could be detected from burials as bone is piezoelectric. Witten et al. (2001) also conducted an initial EM survey to look for mass graves in Tulsa, USA, before follow up magnetic and GPR investigations were undertaken.

Pringle et al. (2008) conducted a controlled experiment in a UK urban garden environment and found that a Geonics™ EM-38 instrument, which is designed to be placed on the ground and therefore should be less susceptible to above-ground interference, did not resolve the target 'grave'. This was attributed to the local urban environment and 'made ground' nature of the burial site. Nobes (1999) also found difficulty using EM methods to locate unmarked graves in a cemetery in New Zealand, due to differentiating anomalies from significant background effects caused by fence boundaries and local topography. Interestingly Nobes (1999) found that the 'head' ends of unmarked graves were easier to identify than the 'foot' ends.

High resolution time-domain EM surveys have also shown promise for unexploded ordnance detection (Pasion et al., 2007). Researchers have also used EM methods to detect landmines (Combrinck, 2001) and buried weapons in a controlled environment (Dionne et al., 2011), although equipment resolution and background variations in soil type can make the detection of small targets problematic.

EM survey equipment needs to be carefully calibrated to the local site conditions and can also be significantly affected by above-ground conductive objects, e.g. metal fences, electricity pylons, cars, etc., which may preclude their use in certain search areas and environments, such as urban areas (see Milsom and Eriksen, 2011; Reynolds, 2011).

Electromagnetic (EM) surveys can be used for environmental forensic geophysical surveys (see Reynolds, 2011), as the target is usually more conductive than background site materials. Bavusi et al. (2006) detail a case study in which an EM survey was used to characterize a waste dump in Southern Italy. Vaudelet et al. (2011) shows an urban contaminant case study characterizing different source sites.

As conductivity surveys using conventional instruments (such as the Geonics™ EM31 or EM38 [Geonics Ltd., Mississauga, Canada]) are directional, they can focus on either the top 5–8 m bgl (using the horizontal model component or HMD) or up to 15 m bgl (using the vertical mode component data or VMD), depending upon the suggested depth of burial bgl and the local site ground conditions.

Electrical methods (resistivity)

Resistivity surveys actively measure the bulk ground resistivity of a volume of material below the sample position (see Reynolds, 2011; Milsom and Eriksen, 2011 for background and operation). Typically, fixed offset resistivity surveys are utilised for searches, due to their relatively rapid coverage of the ground, although Electrical Resistivity Tomography (ERT) 2D profiles have also been collected over simulated clandestine burials (Pringle et al., 2008) and illegal waste dump sites (Ruffell and Kulessa, 2009) which also gives depth information. Basic 2D resistivity modelling can also be undertaken to gain a better understanding of resistivity survey results (see Scott and Hunter, 2004).

Resistivity surveys have the advantage of being less affected by above-ground material (i.e. background 'noise') when compared to EM surveys as probes are shallowly placed into the ground surface. They also work well in clay-rich soil types (see Pringle and Jervis, 2010). However, resistivity survey results can be problematic if undertaken after metal detector search teams have searched for buried items due to disturbances and small voids as detailed by Pringle and Jervis (2010).

Resistivity has been successfully used to locate unmarked burials in cemeteries (e.g. Buck, 2003) and ancient tombs (e.g. Persson and Olofsson, 2004; Powell, 2004; Matias et al., 2006) although local variations in soil moisture content, particularly in heterogeneous ground in relatively dry conditions, can affect survey success by masking target location(s) (Ellwood et al., 1994) and/or result in numerous non-target anomalies being imaged (see Pringle et al., 2012a). Resistivity datasets can also be highly affected by coarse-grained and larger (e.g. cobble) soil types, as well as saline conditions (e.g. Pringle et al., 2012b).

Milsom and Eriksen (2011), however, point out that obtaining data from the area surrounding graves can be problematic due to the inability for probes to penetrate concrete, tarmac or other hard surface.

Resistivity surveys have been successful in locating clandestine graves. Scott and Hunter (2004) and Pringle and Jervis (2010) both detail the use of resistivity surveys in rural Welsh fields in their respective unsuccessful missing person searches. Pringle and Jervis (2010) used semi-quantitative analysis of resistivity data to identify anomaly locations, and compared the results to simulated study results.

Published control studies over simulated burials (e.g. Cheetham, 2005; Jervis et al., 2009) have therefore proved useful for forensic investigators for comparison with active search data; these studies typically used a small grid survey pattern (0.25- to 0.5-m-spaced data point samples) so that targets could be resolved. Low resistivity anomalies with respect to background values would be expected to occur over clandestine burials of murder victims, due to increased soil porosity (Scott and Hunter, 2004) and the presence of highly conductive decomposition fluids (see Jervis et al., 2009; Pringle et al., 2010). However, Jervis et al. (2009) found that high resistivity anomalies, with respect to background values, were observed over clandestine burials with a wrapped pig cadaver, and concluded that the wrapping prevented decomposition fluids being released into the ground and the wrapped cadaver presented a barrier to electrical currents. Juerges et al. (2010) documented that decompositional fluid may be detectable below surface pig remains, even when no physical evidence of the cadaver remained.

Resistivity methods (particularly ERT) are a standard investigatory tool for environmental forensic investigations. Environmental applications of the technique include looking for leachate leaking from landfills (see Reynolds, 2011) and contaminant plumes from urban sites (see Vaudelet et al., 2011), identifying where illegally buried solid waste may be located (Cardarelli and Di Filippo, 2004; Ruffell and Kulessa, 2009) and studying potential aquifer contamination by graveyards (Matias et al., 2004).

Ground penetrating radar (GPR)

Ground penetrating radar (or GPR) is a commonly used near-surface geophysical technique for the detection of unmarked grave locations, clandestine graves and various other buried materials, with radar reflections caused by contrasts in dielectric permittivity. Successive 1D radar traces are collected to build up vertical 2D profiles of the sub-surface, with 3D datasets being collected if time permits (see Jol, 2009 for background theory and operational detail). Commonly bi-static, fixed-offset transmitter-receiver antennae with fixed frequencies are used to acquire a series of 2D profiles.

GPR has arguably one of the highest resolutions of near-surface geophysical survey techniques and data can be obtained relatively quickly, depending upon the equipment, antennae frequency and trace sampling spacing utilised. It is one of the most commonly used techniques for near-surface target detection and widely used in the geotechnical industry for buried utilities (see, for example, Metje et al., 2007). GPR has also been shown to work successfully to locate snow avalanche survivors (see Instanes et al., 2004). However the method does not work well in saline environments due to poor penetration (see Pringle et al., 2012b). There have also been studies showing reduced penetration in damp clay-rich soils although if this is homogenous it is not a big problem (see Nobes, 1999).

Conyers (2006) suggests GPR can detect the disturbed grave back-fill, the coffin itself, its contents and any grave 'fluid', although Nobes (1999) highlights that age of burial is important with associated variability in burial styles and decomposition causing target detection and signature to vary considerably, even within the same burial site. Historical graves can often be difficult (though not impossible) to detect due to the limited skeletal remains and the process of soil compaction (e.g. Vaughan, 1986).

Published clandestine grave searches using GPR include Mellet (1992), Calkin et al. (1995), Davenport (2001), Schultz (2007) and Billinger (2009). Nobes (2000) detailed a GPR survey which followed up on anomalous areas identified in an EM survey looking for a clandestine grave in woodland. Novo et al. (2011) also detail a difficult GPR search for a grave in a mountainous area. For example, Davis et al. (2000) document a GPR survey for unmarked and shallowly buried, Spanish Influenza victims from 1918 in Svalbard, Norway. Ruffell et al. (2009a) showed a GPR case study of mass graves from the Irish 'Potato Famine' in the 19th Century. Ruffell and McKinley (2008) also point out that the additional material in legal graves (coffin, clothes, lime, disinfectant, embalming fluid, etc.) that may prevent results from being comparable to clandestine burials.

Controlled grave studies, whereby animal remains (typically pig cadavers) are used as a proxy for human remains, have been used to determine whether GPR could be successful to locating a target. An early example of this was that of France et al. (1992) a multi-disciplinary study in the USA. Strongman (1992) also published a series of case studies, using 5 year old bear carcasses with comparison to case results. More recent control study examples include sequential GPR monitoring over large (Schultz et al., 2006) and small (Schultz, 2008) pig cadavers and a simulated clandestine grave with accompanying GPR time-slices (Pringle et al., 2008).

There are currently differing views amongst researchers on which set frequency GPR antennae should be utilised for forensic searches. GPR antennae commonly range from 50MHz to 2000 MHz; Ruffell et al. (2009a) suggest 200 MHz was optimal to detect shallow buried unmarked historical graves, and used 400 MHz to image an individual burial, and Schultz and Martin (2011) showed both 250 and 500 MHz antennae could be utilised to detect simulated clandestine graves, whilst others suggest higher frequencies (e.g. Buck, 2003 used 800 MHz frequency GPR antennae to locate unmarked graves). The general consensus seems to be that optimum detection frequency will depend on target size, depth bgl, geology and soil type.

Ruffell (2005b) gives a good review of some of these parameters, showing sandy soils are optimum for GPR surveys; this was also supported by France et al. (1992); although note surveys will always be site specific and depend upon depositional processes. For example, Nobes (2007) detailed five burial sites in New Zealand with different soil types and found sandy soil did not show targets, as depositional processes mimicked grave responses.

High clay content soils and saline conditions (Pringle et al., 2012b) also significantly reduce radar penetration depths. A current major limitation is the speed of data collection that precludes whole fields to be surveyed, and the significant post-field data processing time to optimise datasets. There is research to analyse radar wavelets to assist target detection (see Freeland et al., 2003). There has also been research to numerically model the expected GPR responses from buried human remains in different soil types (Hammon et al., 2000). Cassidy (2007a) reviews GPR numerical modelling methods for a variety of buried targets.

Millington et al. (2011) go further and invert synthetic GPR data from a simulated clandestine grave for automatic target location purposes although this is currently still being developed. Solla et al. (in press) used a different approach using finite-difference time-domain (FDTD) modelling of GPR data acquired over simulated buried forensic objects and used ground-based photogrammetric methods to calibrate the modelling.

Acheroy (2007) reviewed both remote and field detection of antipersonnel mines using GPR methods, EM sensors and remote sensing. He also documented the main current police and military search forensic geophysical detection equipment which are a combination of GPR and metal detectors, with Bruschini et al. (1998) showing a case study of these combined methods. Lopera and Milisavljević (2007) documented how important the knowledge of soil type is to predict the GPR responses from metallic and non-metallic landmines. Furthermore Sato et al. (2004) provided information on the potential for using GPR antennae arrays to obtain common mid-point (CMP) multi-fold datasets for landmine detection, a significant improvement than the typical fixed-offset 2D profiles commonly acquired.

For environmental forensic target detection, there are case studies given in Reynolds (2011), ranging from mapping of contaminated land, pinpointing of illegally buried, toxic waste (see Orlando and Marchesi, 2001; Ruffell and Kulessa, 2009) to mapping groundwater contamination from landfills (Davis and Annan, 1989), chemical (Brewster and Annan, 1994) and hydrocarbon spills (Bermejo et al., 2007; Cassidy, 2007b). These can often be observed by radar signal attenuation and dielectric permittivity contrasts, although note geophysical detection can be temporally variable depending upon contaminant size, concentration and dispersal rates (see Greenhouse et al., 1993; Sauck et al., 1998).

Magnetometry

Highly sensitive magnetometers have had varied success in forensic applications. Ancient archaeological graves have been shown to have high magnetic susceptibility (Linford, 2004), proposed as due to being long-term mineral changes caused by bacterial action. However magnetic results over simulated recent clandestine burials in a variety of depositional environments have proved to be not that useful (see Juerges et al., 2010).

Ellwood (1990) and Witten et al. (2001) encountered difficulties in locating 19th century graves in cemeteries and a mass grave from 1921, respectively, using magnetic methods, although Stanger and Roe (2007) showed fluxgate gradiometry was successful for 20th century graves in an Australian cemetery. Magnetic susceptibility analysis was undertaken on illegally dumped soil on a motorway in China that caused multiple fatalities and successfully identified its origin (Manrong et al., 2009). Hannam and Dearing (2008) used magnetics in Bosnia and Herzegovina for landmine clearance operations.

Pringle et al. (2008) pointed out that magnetic susceptibility datasets can also be used for quality control checking of magnetic gradiometry datasets: e.g. for assisting with the removal of magnetic data spikes.

Recent field trials by the authors have shown magnetic susceptibility methods are optimum to detect buried metallic targets beneath a domestic patio versus total field and gradient methods (see Reynolds, 2011 for background). Magnetic surveys collected by helicopters flying at a low altitude have also proved useful in identifying UXOs; Billings and Wright (2010) provide a good example from a former army range in Canada. For land-based surveys for UXO detection, case studies using specialised magnetometers have been published on multi-sensor 3- axis magnetometers (Munschy et al., 2007), quad-sensor arrays (Billings and Youmans, 2007) and borehole magnetometry (Zhang et al., 2007). However, Butler (2003) details the importance of understanding the background magnetic susceptibility for identifying and locating UXOs and uses case examples from Indiana and Hawaii, USA.

In environmental forensic applications, Marchetti et al. (2002) detail how magnetic methods identified where over 160 illegally buried solid metal drums were located, with a recent paper showing how test sites can aid magnetic data interpretation (Marchetti and Settimi, 2011).

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1.3 CLANDESTINE GRAVES

This work deals with forensic targets consisting on clandestine recent graves: these involve the presence of a body which can present additional effects during the decomposition process.

Because the condition of the body changes over time, a recent grave constitutes a feature with dynamic geophysical properties. Understanding the decomposition dynamics has significant implications in modelling for real scenarios.

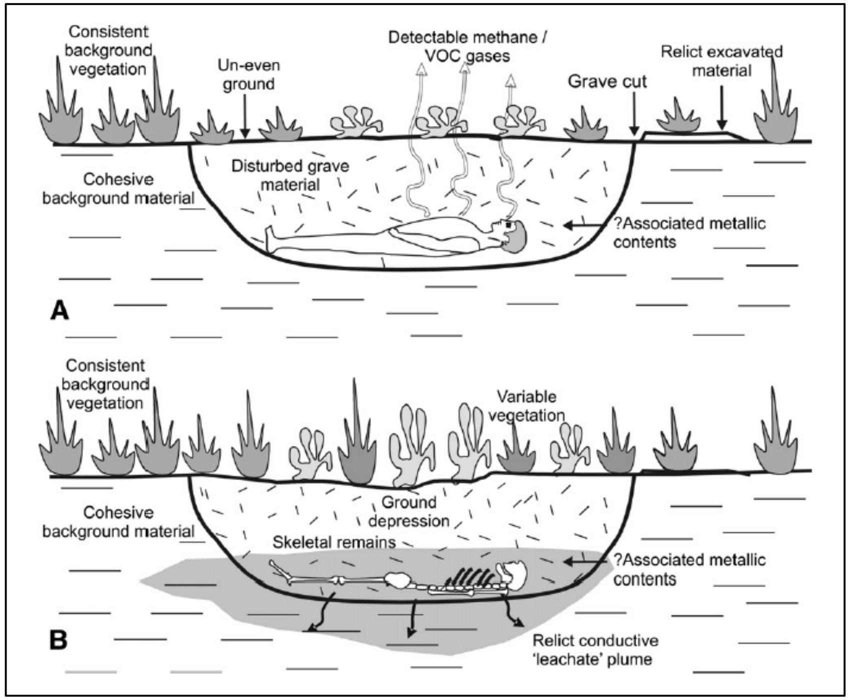
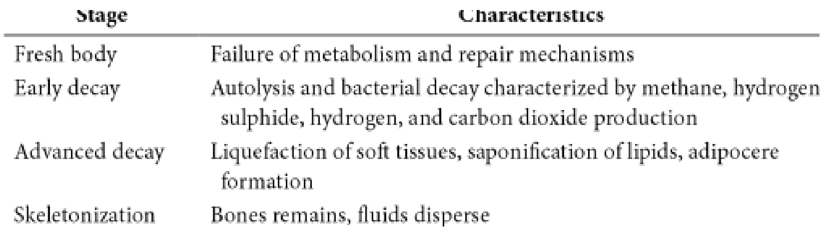


Fig 1.2: An idealized conceptual geological model for a shallow homicide grave (7): (A) recent burial; (B) old burial. Potential location indicators are shown.

Soil provides an aggressive environment that will promote the bio-deterioration of organic materials and the corrosion of most metals.

The breakdown of a cadaver can be summarized by the stages in Table 1.1 (11). During autolysis tissue breakdown is abiotic and is due to the action of internal enzymes released through cell lysis. Putrefaction results in widespread destructive changes due to the metabolism of anaerobic bacteria. This results in conversion of soft tissue into liquids and gases. A soft tissues liquefy, the depositional environment at the base of the grave is chemically and biologically dominated by semiliquid remains. The burial of the cadaver results in a decreased rate of decomposition.



Stage	Characteristics
Fresh body	Failure of metabolism and repair mechanisms
Early decay	Autolysis and bacterial decay characterized by methane, hydrogen sulphide, hydrogen, and carbon dioxide production
Advanced decay	Liquefaction of soft tissues, saponification of lipids, adipocere formation
Skeletonization	Bones remains, fluids disperse

Tab. 1.1: Stages of cadaveric decay (11)

The chemical alteration of soil in the vicinity of a decomposing cadaver can affect the local environment in a number of ways.

The release of decomposition fluids can alter the appearance of soil, as grave soil collected from adjacent to a cadaver can result being blackened, wet and odorous.

Local vegetation may also be affected by the presence of a decomposing cadaver. Cadavers at the surface may initially result in a loss of plant life due to smothering by the body or the leached decomposition products (31). Subsequently, opportunistic plants may colonise the site of the cadaver site (31), as they utilise the nutrients (such as nitrogen and carbon) released by a decomposing cadaver, which may lead to enhanced plant growth at the cadaver location.

Cadaver decomposition can also affect soil ecology. Increases in soil microbial biomass and microbial activity have been observed in soil collected from adjacent to buried cadavers (11). Increased microbial activity is suggested to be the cause of temperature increases within a grave: Increases as large as 10°C within shallow (0.3 m deep) graves have been observed (32).

Aspects related to the process of decomposition of human remains which can interfere with geophysical investigations are:

- the presence of the body itself: initially the content of water is predominant, then liquids percolate gradually and spread into the soil till skeletonization, when the role played by the presence of bones is predominant(11);
- the high conductive nature of decomposition fluids: this causes a strong modification of the burial environment (10);
- the presence of clothing or overlying materials: this can prevent the body from decomposition acted by insect and can constitute an anomaly itself (9);
- the presence of a range of materials accompanying the body such as tools and weapons (26);
- the progressive failure of the bony structures creates cavities that can be anomalous in the burial environment (28);
- the time since burial has been shown to have a big effect on the geophysical response (Fig. 1.2);
- the disturbance caused by digging the grave and the less consolidated fill that results, will contribute to a grave's geophysical properties.

All of these issues will be kept in count in the experimental investigation over the test of the specific case study. Clandestine grave is defined in this study as an unrecorded burial that has been hand-excavated and has been dug <1 m depth below ground level (bgl). There has been little published quantitative data on discovered clandestine burial dimensions.

Hunter and Cox (4) detailed 29 U.K. cases, where discovered burial depths bgl averaged 0.4 m and Manhein (5) reports 87 discovered burials in U.S. with average depth of 0.6 m. All of them are usually rectangular in plan-view, with burials mostly hurriedly hand-dug using garden implements and dimensions usually just large enough to deposit the victim before back-filling with excavated soil and associated surface plant debris.

CHAPTER 2

CASE STUDY:
TIME LAPSE GEOPHYSICAL MONITORING OF SIMULATED CLANDESTINE GRAVES USING ELECTRIC METHODS

2.1 AIMS OF THE MONITORING RESEARCH

The experimental work of this thesis is involved in a long-term monitoring project on the response of simulated burials to geophysical investigation techniques: 2013 is the sixth year of monitoring activity.

As stated in the previous chapter, geophysical surveys have been applied to locate clandestine graves in a number of reported criminal investigations searches in UK. In fact the forensic target generates a contrast of physical properties between the target itself and the media in which it is buried. Any change in physical properties of the ground caused by a grave might be brought by a wide variety of different causes, and it is important to be aware of these and their potential magnitude in order to assess the applicability of the technique to a particular site.

Electrical resistivity methods were selected because these have not been employed much to date in active search cases, but they have been shown to detect clandestine graves in different ground conditions. GPR is typically the most popular for clandestine grave detection, but electrical methods are a useful alternative. There is a need for forensic geophysical datasets to be collected over known burial site(s) and for the collection of geophysical data over varying time periods post-burial. This would assist forensic practitioners to decide which technique to use for specific sites, based on the geophysical response of the known graves and how this changes over time.

This thesis aims to gain a better understanding of how clandestine graves can be detected by resistivity surveys in terms of:

- type,
- extent,
- temporal horizon

of modifications of the physical properties of the target and the site induced by the time elapsed since the burial. These modifications are anomalies determined by simulated clandestine burials, so that they are detectable by geophysical resistivity surveys in the near surface.

Regular geophysical monitoring of simulated clandestine burials, using pig cadavers on a test site, allows predictions of the potential anomaly size and magnitude to be made with respect to background values, over time.

Documenting temporal changes is important as geophysical responses from recent clandestine burials are known to vary. Potential reasons could be the temporal changes in grave soil characteristics, decomposition products, climatic variations, and other site-specific factors. Experimentation over the longer term is required in order to identify the effect of these variables on the data.

Survey site need to be fully characterized (e.g., geologically and climatologically) to allow comparisons with other studies or indeed for active forensic cases.

2.2 STUDY SITE LOCATION AND DESCRIPTION

The experimental work involved in this thesis has been carried out entirely at Keele University, who currently has a leading role in research in the field of geophysical surveys in shallow target for forensic. Keele University is located close to the town of Newcastle-under-Lyme, in the county of Staffordshire, U.K. (Fig. 2.1). Keele University has advanced technological equipment and a site survey created specifically for the purpose of commercial software and standard processing geophysics.

Figure 2.1: Geographical location of the study site: Keele University, Staffordshire, UK

The local climate is temperate, which is typical for the United Kingdom, without dry season and with warm summer ('Cfb' in Köppen climate classification, 27). The local bedrock is the Keele formation (British Geological Survey, 1994), which consists mostly of sandstone, although some mudstone layers are also present. The drift geology of the area is predominantly till (British Geological Survey, 1994).

The exact site chosen for the study was a 25 m by 25 m plot of land within the 'Walled Garden' (Fig. 2.2).

Data from an engineering borehole, which was situated approximately 150 m from the study site, show the subsurface to be multiple layers made ground to a depth of 1.5 m, below which sandstone bedrock is present; (Fig. 2.2). Observations made during the excavation of the graves at the study site suggested that the soil profile is similar to that described in the borehole data.

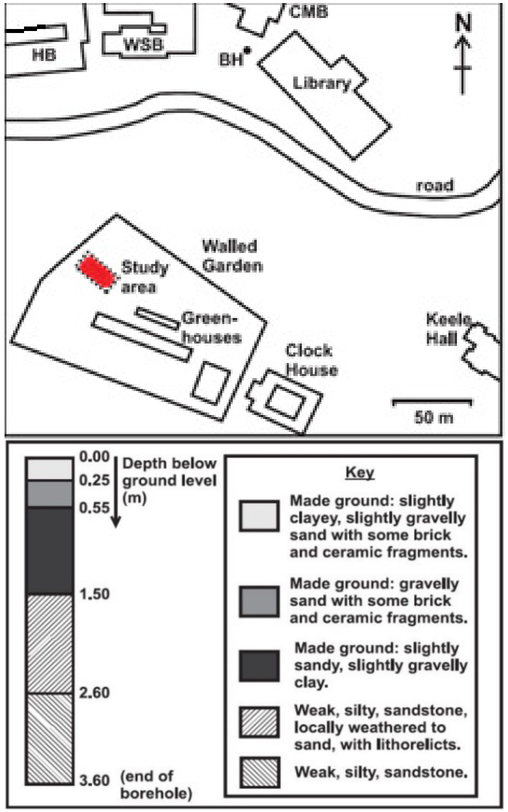


Figure 2.2: Study area localization and borehole scheme (9)

The soil was observed to be a dark reddish brown (Munsell colour: 5 YR 3/3) colour, and occasional sandstone fragments were encountered at a depth of approximately 0.5 m below ground level, which suggests that the bedrock was present at a shallower depth at the study site than at the borehole location. Further evidence for the presence of shallow bedrock at the study site includes a sandstone outcrop just outside the Walled Garden (close to the Clock House, marked on Fig. 2.2). No groundwater was encountered in the engineering borehole. This suggests that, at the time the borehole work was conducted (5th September 2005), the water table was deeper than the maximum borehole depth of 3.6 m.

Figure 2.3: Study area view (March 2013)

The study site is covered by grass and is bordered on three sides by trees (Fig. 2.3), which are predominantly common hazel (*Corylus avellana*) and wild privet (*Lingstrum vulgare*).

2.3 SIMULATED GRAVES AND TEST SITE

A clandestine grave is defined in this study as an unrecorded burial that has been hand-excavated and has been dug <1 m depth below ground level (bgl). Geophysical surveys over simulated clandestine graves provide useful results, as the target size, age and location are known.

The Human Tissue Act (2004) prevents human cadavers from being used for research in the United Kingdom. Domestic pigs carcasses, sourced from a local abattoir, were instead used as proxies to simulate homicide victims, after the necessary permissions from the U.K.'s Department for Environment, Food and Rural Affairs had been obtained. Pig cadavers are commonly used in such monitoring experiments as they comprise similar chemical compositions, size, tissue: body fat ratios, and skin / hair type to humans.

A total of five graves were created at the study site:

- three for the purpose of being geophysically surveyed. They are located in a 5 m ·14 m area, sloped by c. 3° from NW to SE. The first grave contained a pig cadaver (henceforth referred to as the 'naked pig' grave), the second grave contained only the soil that had been removed during the excavation of the hole ('empty' grave), and the third grave contained a pig cadaver wrapped in tarpaulin ('wrapped pig' grave);

- two graves were created for the collection of soil and soil-water samples: an additional pig grave ('second pig grave') and an additional empty grave ('second empty grave'). The 'second pig grave' and the 'second empty grave' were created to be as similar to the 'naked pig grave' and the 'empty grave', respectively, as was possible.

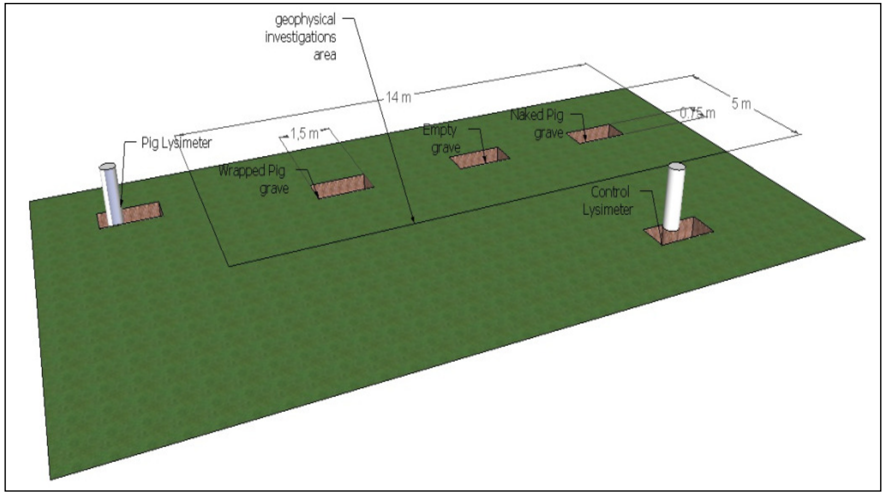


Figure 2.4: Study area scheme

The 'empty grave' and the second empty grave were created on the 6th of December 2007. For both graves, the turf was removed and a hole, measuring approximately 1.5 m long, 0.75 m wide and 0.6 m deep, was excavated using shovels. The holes were then refilled with the excavated soil, which was tamped down until level with the surrounding ground, and the turf was replaced. Not all of the excavated soil could be returned to the empty graves, and some soil was disposed of away from the study site in the Walled Garden. A lysimeter was also installed in the 'second empty grave', for the purpose of collecting water samples.

The 'naked pig' grave, the 'second pig grave' and the 'wrapped pig' grave were created on the 7th December, 2007. The pig cadavers, which weighed approximately 80 kg each, were collected from a local abattoir on the day that the graves were created. At the time of collection, the pigs had been dead for less than 24 hours. The pig grave and the second pig grave were created in the same manner as the empty graves, except that a pig cadaver was placed in the open grave prior to backfilling of the soil. A lysimeter was also installed in the second pig grave.

The wrapped pig grave was created in the same manner as the pig grave, except that the cadaver was wrapped in tarpaulin prior to being placed in the grave. The tarpaulin measured 1.8 m by 2.7 m, and was made of woven, 3 mm wide, polyethylene strands (Duratool Corporation, product no.: D00065). All graves had their long axes orientated in an approximately northwest to south-east direction (Fig. 2.4).

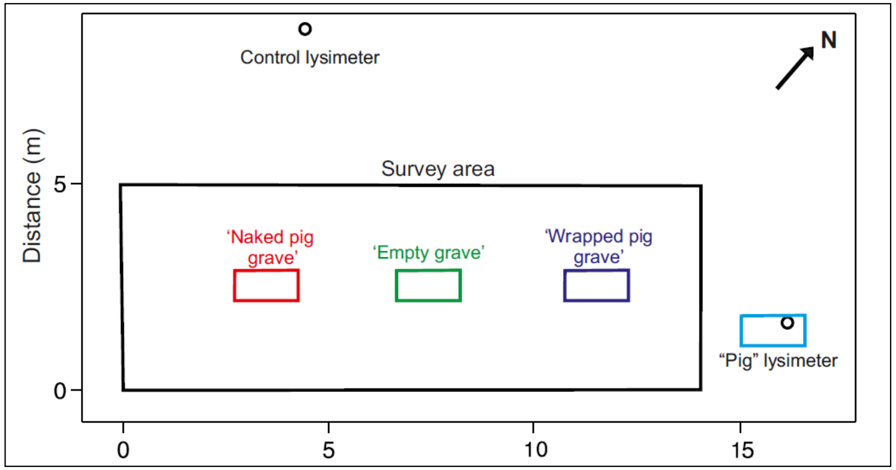


Figure 2.5: Study area scheme

The dimensions of the graves and the size of the pigs were evaluated keeping in count UK and US clandestine burial statistics (Section 2.3).

2.4 GEOPHYSICAL TECHNIQUES & THEORETICAL PRINCIPLES

Within this project Electrical Resistivity and GPR techniques have been deployed to investigate simulated graves located in test site.

Electrical resistivity methods were selected because these have not been employed much to date in active search cases, but they have been shown to detect clandestine graves in different ground conditions. However, geophysical responses will vary depending upon local soil type; therefore, resistivity surveys will not be applicable in all searches.

The development of other geophysical techniques of forensic investigation has caused a re-evaluation of GPR in comparison with other devices, despite many of the early problems have now been solved.
Likewise many studies now deploy two or more geophysical techniques along the same survey lines, specifically to overcome individual problems of acquisition in one or other method. GPR data sets at the commonly acquired (110–900 MHz) frequencies were also collected for comparison purposes.

It was deemed unnecessary to collect magnetic data as, in contrast to historical graves that do show anomalies, magnetic results over simulated recent clandestine burials in a variety of depositional environments have proved to be unpromising for search teams (28).

This thesis focuses on geophysical techniques investigating the electrical resistivity of the ground and its modifications induced by the presence of a grave as forensic target.

2.4.1 Electrical Resistivity Surveys

In reality, the subsurface does not conform to a homogeneous medium and thus the resistivity obtained by measures is apparent ground resistivity ρ_a which can even be negative and is not a physical property of the sub-surface media unlike *true resistivity*. Only interpretation techniques lead to 'true' resistivity.

Most rock-forming minerals are very poor conductors, and ground currents are therefore carried mainly by ions in the pore waters. Pure water is ionized to only a very small extent and the electrical resistivity of pore waters (or groundwater) depends on the presence of dissolved salts.

Electrical resistivity quantifies how strongly a given material opposes the flow of electric current. If there is electric field inside a material, it will cause electric current to flow. The electrical resistivity ρ is defined as the ratio of the electric field to the density of the current it creates inside the conductor:

$$\rho = \frac{E}{J}$$

where:
ρ is the resistivity of the conductor material (measured in ohm-meter, Ω·m),
E is the magnitude of the electric field (in volts per meter, $V \cdot m^{-1}$),
J is the magnitude of the current density (in amperes per square meter, $A \cdot m^{-2}$),

To understand how resistivity surveys are capable of detecting clandestine graves, it is necessary to appreciate which soil properties influence the resistivity of the ground (17). Groundwater conductivity (σ_w) and the soil volumetric water content (θ) are considered to be the factors that exert the most influence on the electrical resistivity of soil.

The general form of the equation for apparent soil conductivity (σ_a; the inverse of soil resistivity) is

$$\sigma_a = \rho_a^{-1} = F_G(\theta)\theta\,\sigma_W + \sigma_s \qquad \text{(Eq.1)}$$

where the function $F_G(\theta)$ describes the pore water geometry and σ_s accounts for conductivity due to ion exchanges at the interface between groundwater and the soil particles. $F_G(\theta)$ has not yet been formulated exactly but suitable approximations include a power function of θ and a function of soil porosity (θ_{sat}) as well as θ.

A soil with a high percentage of sand and/or gravel that drains quickly would register a higher resistivity, whereas a more clayey or silty soil will retain moisture, act as a conductor and register a much lower resistivity, its smaller grain size contributes to the conductivity by providing a higher probe contact surface area .

From Equation 1 it is clear that changes in either soil volumetric moisture content or groundwater conductivity could satisfactorily explain changes in the resistivity of the ground within a grave. In fact these two phenomena can be determined by the body concealment and decomposition.

The 'obvious' method of measuring ground resistivity by simultaneously passing current and measuring voltage between a single pair of grounded electrodes does not work, because of contact resistances that depend on such things as ground moisture and contact area and which may amount to thousands of ohms. The problem can be avoided if voltage measurements are made between a second pair of electrodes using a high-impedance voltmeter. Such a voltmeter draws virtually no current, and the voltage drop through the electrodes is therefore negligible.

Surveys involving direct injection via electrodes in the ground surface are generally referred to as Direct Current or *DC* surveys, even though in practice the direction of current is reversed at regular intervals (1 or 2 seconds) to cancel some forms of natural background noise.

The electrical measurement is the resistance value of a completely homogeneous ground that would produce the same result when investigated in exactly the same way. This quantity is transformed in electrical resistivity as the product of a measured resistance R (units Ω) and a geometric factor K (units m) for a given electrode array. The result is known as the apparent resistivity ρ_a and has the unit of ohm-meters (Ωm):

$$\rho_a = RK \qquad \text{(Eq.2)}$$

For a current source and sink the potential at any point in the ground is equal to the sum of the voltages from the two electrodes (+ and -).

Figure 2.6 shows the generalized scheme of an Electrical Resistivity Survey: electrical current intensity I (in mA) is applied by the transmitter T_X between the current electrodes A and B, I_{AB}. It generates a potential difference (in Volts) in the ground which is measured by the receiver R_X between the potential electrodes M and N, V_{MN}.

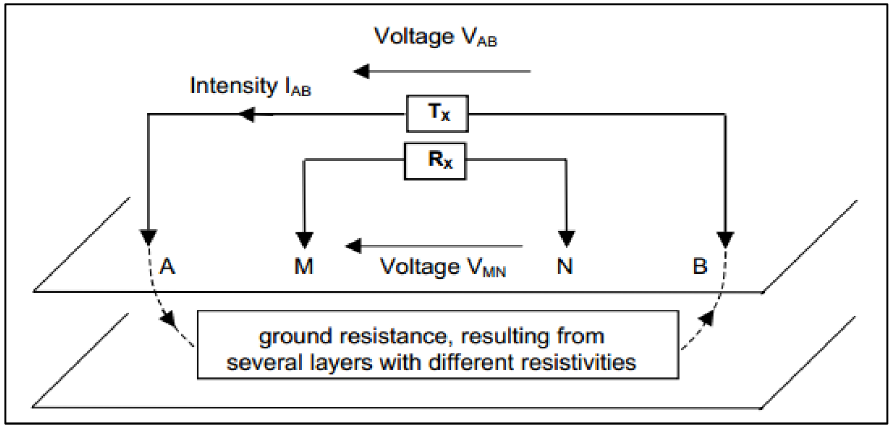


Fig. 2.6: generalized scheme of Electrical Resistivity Survey.

Resistance R between potential electrodes M and N is the result of Ohm's Law:

$$R = \frac{\delta V}{I} \qquad \text{(Eq. 3)}$$

where $\delta \mathrm{V} = V_{MN} = V_M - V_N$ and $I = I_{AB}$.

By Equation 2 potentials at electrode M and N can be calculated as:

$$V_M = \frac{\rho_a I}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB}\right] \qquad V_N = \frac{\rho_a I}{2\pi}\left[\frac{1}{AN} - \frac{1}{NB}\right]$$

So the potential difference can be rewritten as:

$$V_{MN} = V_M - V_N = \frac{\rho_a I}{2\pi}\left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\}$$

Rearranging this so that apparent resistivity is:

$$\rho_a = \frac{V_{MN}}{I} 2\pi \left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\} = RK \qquad \text{(Eq. 4)}$$

This final expression (Eq.4) is composed by two parts: a resistance term R and a term that describes the geometry of the electrode configuration being used, known as the geometric factor K. This geometric factor takes into account the geometric spreads of the electrodes and contributes a term that has the unit of length (m).

The geometric factor K is consequently defined by Equation 5:

$$K = 2\pi \left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]^{-1} \qquad \text{(Eq. 5)}$$

in which the terms depend on the electrodes configuration (distances between electrodes in meters).

There are many types of electrode array configurations: different type and styles of electrode configuration have particular advantages, disadvantages and sensitivities Factors affecting the choice of array type include the amount of space available to lay out an array and the labor-intensity of each method (14). Other important considerations are the sensitivity to lateral inhomogeneity and to dipping interfaces and depth penetration, which is almost impossible to define because the depth of which a given fraction of current penetrates depends on the layering as well as the separation between current probes.

Resistivity surveying can generate two types of result:

- a vertical sounding of resistivity, where depths to different layers can be interpolated, known as *Electrical Resistivity Image (ERI);*

- a plan view of the horizontal changes in resistivity, as the *Constant Offset Electrical Resistivity Survey.*

2.4.1.1 Constant Offset Resistivity Surveys

In resistivity mapping the technique is to take readings of ground resistance at set spacing on a grid and then to contour the values obtained.

The twin probes array was chosen for this study as this array has been proven to be capable of detecting clandestine graves (13). This type of array is commonly used in archaeological mapping as it is easier to use than the Wenner array, because only two electrodes need to be moved with every reading. It also produces much simpler anomalies which can be more easily identified in a noisy environment. Electrode array scheme is displayed in Figure 2.7 and it is also known as pole-pole array. In practice the ideal pole-pole array, with only one current and one potential electrode does not exist.

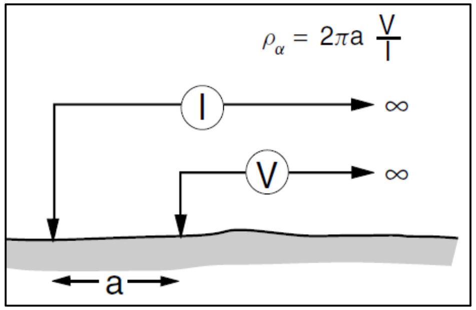


Fig. 2.7: Twin probes electrode array (12)

The twin probes array has four probes (Fig. 2.9):

- mobile probes: one current and one voltage probes are mounted on a mobile frame to collect survey readings,
- remote probes: the other current and voltage probes are placed remotely. These fixed remote probes are connected to the mobile survey probes by a trailing cable.

To approximate the ideal pole-pole array, the second current and potential electrodes must be placed at a distance that is more than 20 times the maximum separation between the mobile electrodes used in the survey. The long cables required can impede field work and may also act as aerials, picking up stray electromagnetic signals (inductive noise) that can affect the readings.

This array has the widest horizontal coverage and the deepest depth of investigation. However, it has the poorest depth resolution, which is reflected by the comparatively large spacing between the contours in the sensitivity function plot (Figure 2.8). Near-surface effects may be large when a twin probes array is used for profiling but are also very local. A smoothing filter can be applied.

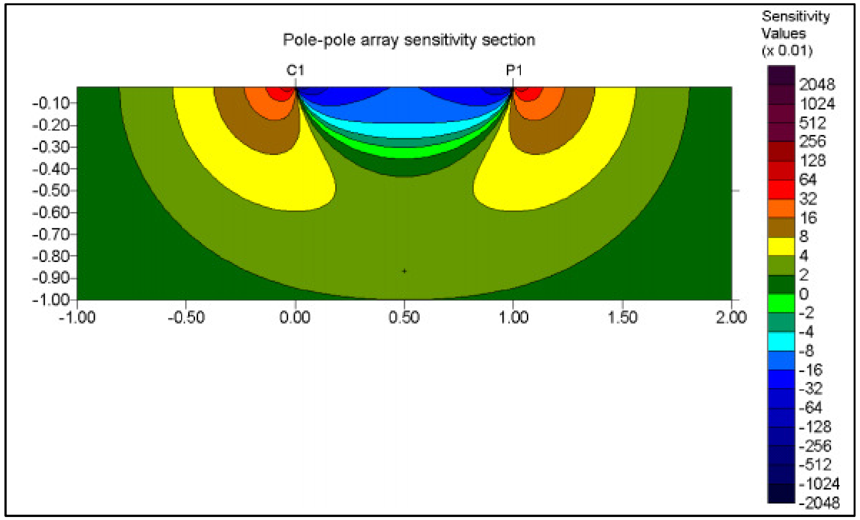


Fig. 2.8: 2-D sensitivity sections for Pole-Pole array. C for 'current electrode', P for 'potential electrode'

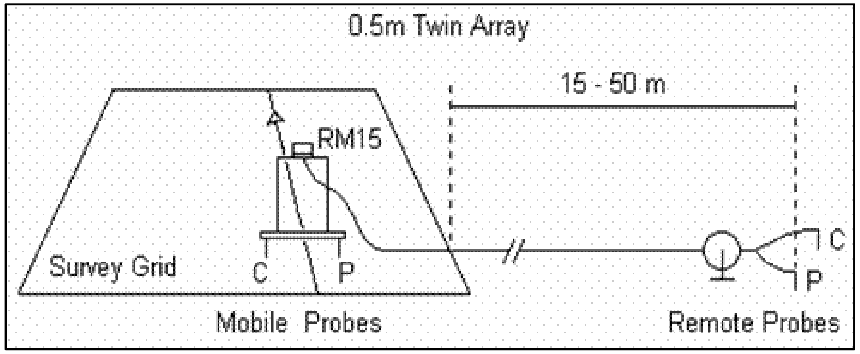


Fig. 2.9: Twin probes electrodes array scheme

The resistance meter measures the electrical potential V [V] due to the passing of an electrical current I [A] in the ground, so the electrical resistance R [Ω] is then calculate by Ohm's Law (Eq. 3). Then it automatically stores the values of the grid.

It is important to assess the resistivity variation over a site in order to determine whether a spatially small variation in resistivity of this magnitude would be visible.
Scott & Hunter (15) tried to compare the contrast due to the grave with the resistivity variation produced by the surrounding environment in order to ascertain whether the grave anomaly could be located within its background. They assumed a very simple grave model: in cross-section the grave model is considerd to be 40 cm deep by 50 cm wide (Fig. 2.10). It was assumed that digging the grave has increased the porosity of the surrounding sandy soil from 20% to 40% and that the soil is fully saturated with water of 10Ωm resistivity.

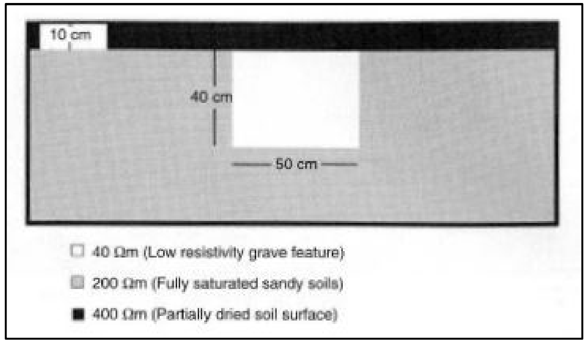


Fig. 2.10: Scott & Hunter's simple model for a grave (15)

Thin (10cm) partially saturated soil covers the surface with a higher resistivity. The resistivity of the fully saturated ground can be estimated using the Winsauer equation:

$$\rho_{ground} = \frac{0.62\ \rho_{water}}{Porosity^{2.15}} \qquad \text{(Eq. 6)}$$

which has been proposed as a model for unconsolidated sediment (20).The apparent resistivity measured by using the pole-pole array at 50 cm spacing can be calculated by using the program Res2Dmod and the results of this are given in (Fig. 2.11).

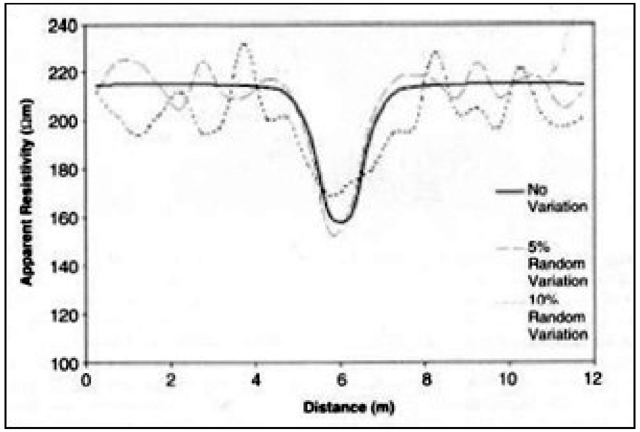


Fig. 2.11: Scott & Hunter's resistivity variation caused by a model grave (15)

Some random noise has been added to the data in order to make the anomaly more realistic. It can been seen that the spatial distribution of the anomaly is just visible above the 10% added noise. However 20% noise due to environmental variation would be of the same magnitude of the anomaly.
The anomaly results of the same magnitude to anomalies measured over a test site consisting of pig burials (19).

2.4.1.2 Electrical Resistivity Imaging – ERI

The aim of these geophysical surveys is to obtain true resistivity models for the sub-surface because it is these that have geological meaning.

In electrical resistivity imaging a vertical section of the true resistivity is created using an array of multiple electrodes connected to a microprocessor by a multicore cable. Using software control, discrete sets of four electrodes can be selected in a variety of electrode configurations and separations and a measurement of the resistance made for each.

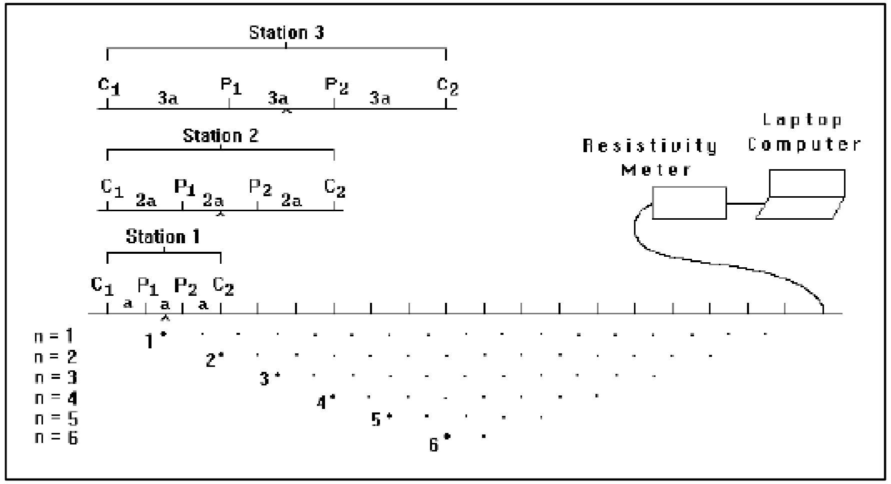


Fig. 2.12: Measurement sequence scheme for building up a resistivity pseudo-section (14)

Figure 2.12 explains how the system works: starting with the shortest electrode spacing (Station 1, n=1), it is addressed and a value of apparent resistivity obtained (point 1). Successive sets of four electrodes are addressed, shifting each time by one electrode separation laterally. Once the entire array has been scanned, the electrode separation is doubled (n=2) and the process repeated until the appropriate number of levels has been scanned. The values of apparent resistivity obtained from each measurement are plotted on a pseudo-section and contoured.

A field curve is produced for each sounding along the array and interpreted by computer methods to produce a geo electric model of true layer resistivity and thickness (Fig 2.13).

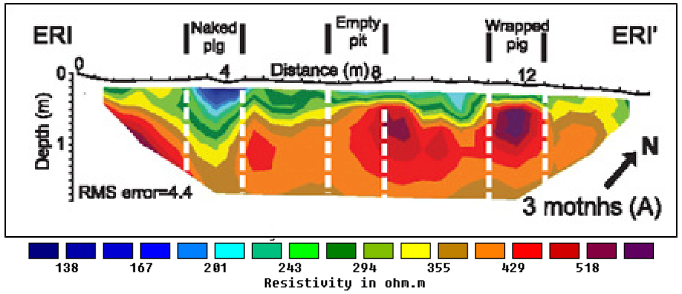


Fig. 2.13: Example of a ERI final result.

For this investigation technique, a Wenner electrode configuration was deployed (Fig.2.14). It is very widely used, and supported by a vast amount of interpretational literature and computer packages. In general, the Wenner is good in resolving vertical changes (i.e. horizontal structures), but relatively poor in detecting horizontal changes (i.e. narrow vertical structures): this is reflected by the comparatively narrow spacing between the contours in the sensitivity function plot (Figure 2.15). The signal strength is inversely proportional to the geometric factor used to calculate the apparent resistivity value for the array.

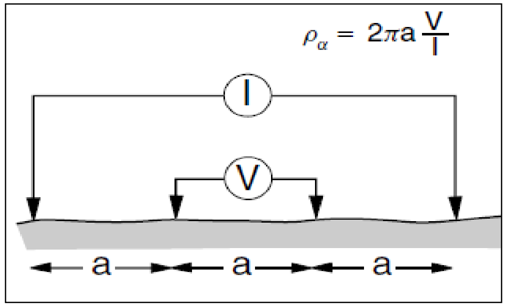


Fig. 2.14 Wenner electrode array (12)

The geometric factor for the Wenner array is 2πa. Among the common arrays, the Wenner array has the strongest signal strength. This can be an important factor if the survey is carried in areas with high background noise.

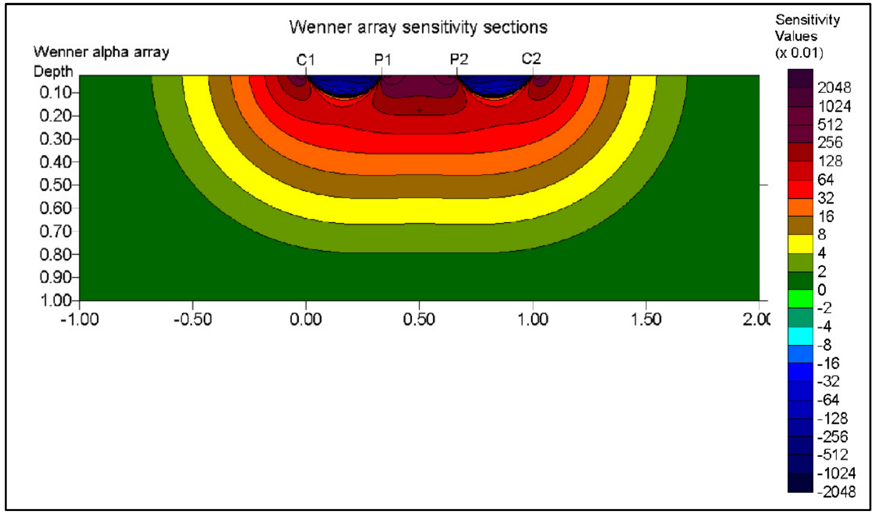


Fig. 2.15: 2-D sensitivity sections for Wenner array. C for 'current electrode', P for 'potential electrode'

CHAPTER 3

DATA COLLECTION

3.1 GEOPHYSICAL FIELDWORK

Desk study work always comes before fieldwork: information about the site should be collected before field work to assess what is the best geophysical method and the survey scheme should be designed according to the target and the potential disturbances. Every survey must be planned according to some strategy, or else it will become an uncordinated muddle. The mere acquisition of data does not guarantee the success of the survey: masses of data does not automatically increase our understanding of a site (12).

The success of a geophysical method can be very site-specific and scientifically designed trials of adequate duration may be very worthwhile to provide confidence that the technique chosen will work or that the survey design needs modifying in order to optimise the main survey.

Potential geophysical disturbances such as metal objects, boundaries or trees and their related root system should be identified and their contribute to results should be predicted. Contingencies can significantly extend the duration of the acquisition and therefore it causes negative economic impacts. Good use is to check the battery charge, the weather forecast and make sure to pick up everything is needed before leaving for the test site.

A strong constrain to geophysical survey is the weather. Some types of survey cannot be deployed on rainy days. For example, electrical methods that rely on direct or close contact with the ground generally do not work in the rain. Other types of survey can continue, since most geophysical instruments are supposed to be waterproof and some actually are.

However, unless dry weather can be guaranteed, a field equipment should be plentifully supplied with plastic bags and sheeting to protect instruments, and paper towels for drying them. Large transparent plastic bags can often be used to enclose instruments completely while they are being used, but even then condensation may create new conductive paths, leading to drift and erratic behavior. Also very low temperatures can inhibit the operation of process units: for example, during the ERI acquisition session on March 2013 the process unit was not able to work due to the low temperatures. It was deemed necessary to warm it up.

With the corners of the grids as known reference points, the instrument operator should prepare and use tapes or marked ropes as a guide when collecting data. In this way, positioning error can be kept to within a few centimeters for high-resolution mapping.

Early surveys recorded readings by hand, but computer controlled data logging and storage are now the norm. When the survey is involved in a long-term monitoring activity is important to effectively catalogue geophysical data, and to store them safely.

3.2 CONSTANT OFFSET RESISTANCE SURVEY

3.2.1 Equipment, array and spacing

In resistivity mapping it is common to take readings of ground resistance at set spacing on a grid and then to contour the values obtained.

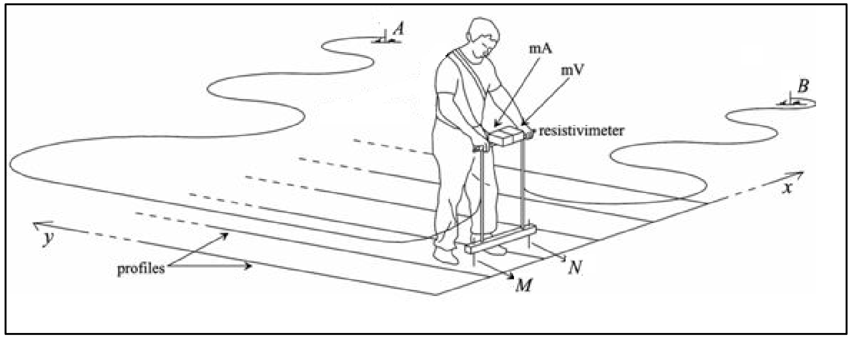
Figure 3.1: Custom built frame used for constant offset resistivity survey

The resistance meter measures the electrical potential V [V] due to the passing of an electrical current I [A] in the ground, so the electrical resistance R [Ω] is then calculate by Ohm's Law.

Resistivity data were collected for the first year with an RM4 resistance meter (Geoscan^{TM} Research, Bradford, UK). From year 1 onward, a RM15 Geoscan^{TM} Research) resistivity meter was used, with the same equipment configuration and collection strategy as stated for the RM4.

A pole-pole electrodes array has been used:

- remote probes were placed 1 m apart at a distance of 17 m from the survey area at the same position for each survey and were inserted c. 0.15 m into the ground;
- mobile probes were set 0.5 m apart and fixed with the resistance meter in a custom-built frame that featured two 0.1-m-long stainless steel electrodes (Fig.3.1).



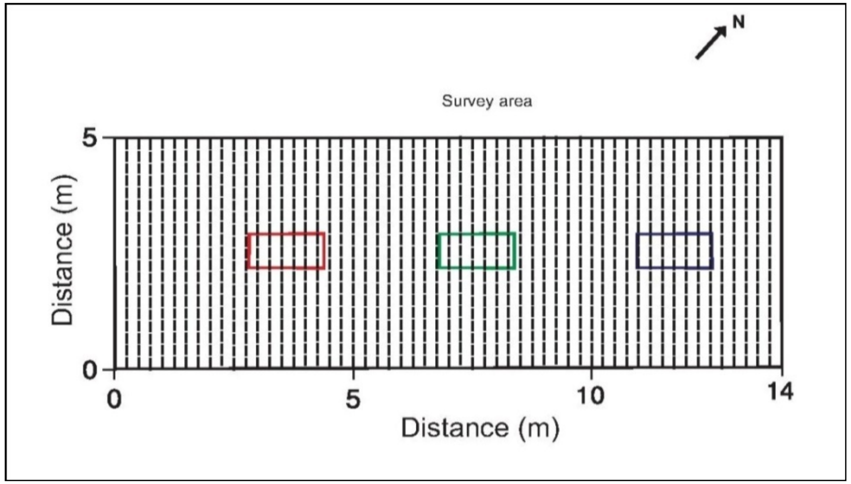


Figure 3.2: Constant offset resistivity survey acquisition scheme. 'Naked pig grave'in red, 'Empty grave' in green, 'Wrapped pig grave' in blue.

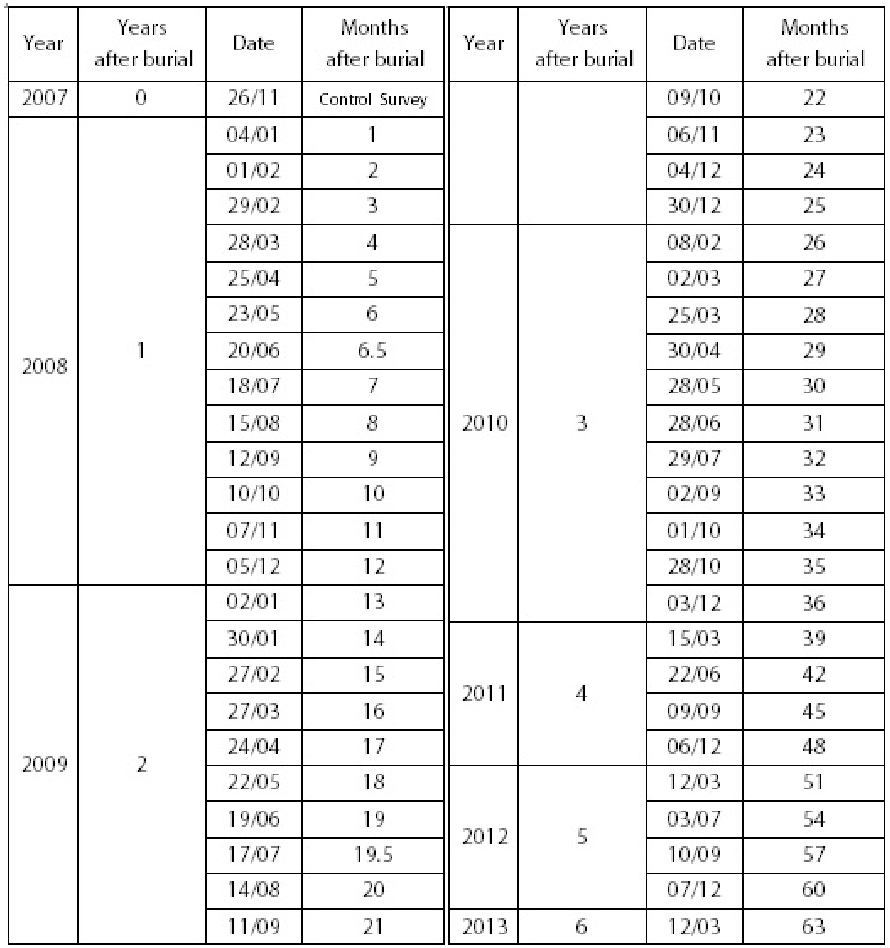
For each measurement, the mobile probes are pushed c. 0.05 m into the ground. Readings are taken automatically a short time after the electrodes are pushed into the surface and when the surface is complete, downloading and display of data takes few minutes.

The survey area measures 5 m • 14 m and sloped by c. 3° from northwest to southeast. In each survey, parallel resistivity measurements were made at 0.25 m intervals along the SE-NW orientated, 5 m long survey lines that were 0.25 m apart, 57 lines in total (Fig. 3.2).

Both ends of each survey line were permanently marked with plastic pegs to ensure that the area surveyed remained constant. Two more pegs permanently marked the reference probe locations. The survey took ~2 hours.

3.2.2 Monitoring activity

A resistivity survey was conducted at the study site 10 days before burial for comparison with the post-burial data sets (Control Survey). Subsequent fixed-offset resistivity surveys were conducted at monthly intervals, commencing 28 days after burial (Table 3.1). From year 3 onward, resistance measurements were taken each 3 months.



Year	Years after burial	Date	Months after burial
2007	0	26/11	Control Survey
2008	1	04/01	1
		01/02	2
		29/02	3
		28/03	4
		25/04	5
		23/05	6
		20/06	6.5
		18/07	7
		15/08	8
		12/09	9
		10/10	10
		07/11	11
		05/12	12
2009	2	02/01	13
		30/01	14
		27/02	15
		27/03	16
		24/04	17
		22/05	18
		19/06	19
		17/07	19.5
		14/08	20
		11/09	21
		09/10	22
		06/11	23
		04/12	24
		30/12	25
2010	3	08/02	26
		02/03	27
		25/03	28
		30/04	29
		28/05	30
		28/06	31
		29/07	32
		02/09	33
		01/10	34
		28/10	35
		03/12	36
2011	4	15/03	39
		22/06	42
		09/09	45
		06/12	48
2012	5	12/03	51
		03/07	54
		10/09	57
		07/12	60
2013	6	12/03	63

Tab. 3.1: Constant offset resistivity survey monitoring activity

3.2.3 Relevant aspects about data collection

It should be remarked that what is measured is the electrical resistance and that, depending on the electrodes configuration used, apparent resistivity values are calculated. Being a monitoring activity, applying the same equipment configuration and collection strategy it’s of fundamental importance.

The electrode separation of 0.5m and the grid spacing of 0.25m were necessary to ensure ground resistance readings would characterize any anomaly caused by a feature as small as a single grave with a spatial extent of less than 1 m^2. It may be necessary to have even smaller spacing, although smaller electrode separations are highly affected by near surface ground variation and smaller grid spacing will increase the survey time.

Care should be taken, however, to ensure any resistivity anomalies were not due to any small rocks or metal detector team digging holes encountered during surveying; where necessary sample positions were not acquired or were re-acquired.

Erroneous readings are usually due to poor ground contact: in fact, the largest source of field problems is the electrode contact resistance. Resistivity methods rely on being able to apply current into the ground. If the resistance of the current becomes anomalously high, the applied current may fall to zero and the measurements will fail. High contact resistances are particularly common when the surface material into which the electrodes are implanted consists of dry sand, boulders, gravel, frozen ground, ice or laterite. The method commonly used to solve the problem is to wet the current electrodes with water or saline solution.

Is fundamental to evaluate the distance of the electrodes with respect to the depth of investigation. Greater electrode separations resulting in current flowing at greater depth. Consequently, the electrode separation used depends on the aim of a survey and may range from a few centimeters to several hundred meters.

In case of Pole-Pole electrode configuration the median depth of investigation (red arrow) is is approximately the electrode spacing (Fig. 3.3).

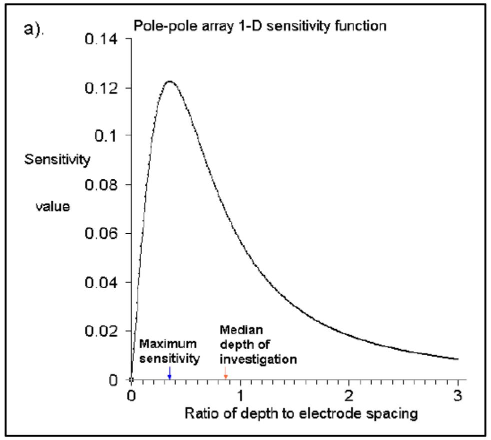


Fig. 3.3: A plot of the 1-D sensitivity function for the pole-pole array.

Noise enters the apparent resistivity values almost entirely via the voltage measurements, so the ultimate limit is determined by voltmeter sensitivity. There may also be noise due to induction in the cables and also to natural voltages, which may vary with time and so be incompletely cancelled by reversing the current flow and averaging. Large separations and long cables should be avoided if possible, but the most effective method of improving signal/noise ratio is to increase the signal strength.

3.3 ELECTRICAL RESISTIVITY IMAGING - ERI

3.3.1 Equipment, array and spacing

A 2D ERI survey line orientated SW-NE (Fig.3.3) which bisected all three graves was permanently marked with plastic pegs and surveyed. It was a15.5 m long survey profile, with 32 • 0.3 m long stainless steel electrodes placed ~0.1 m into the ground every 0.5 m along the profile.

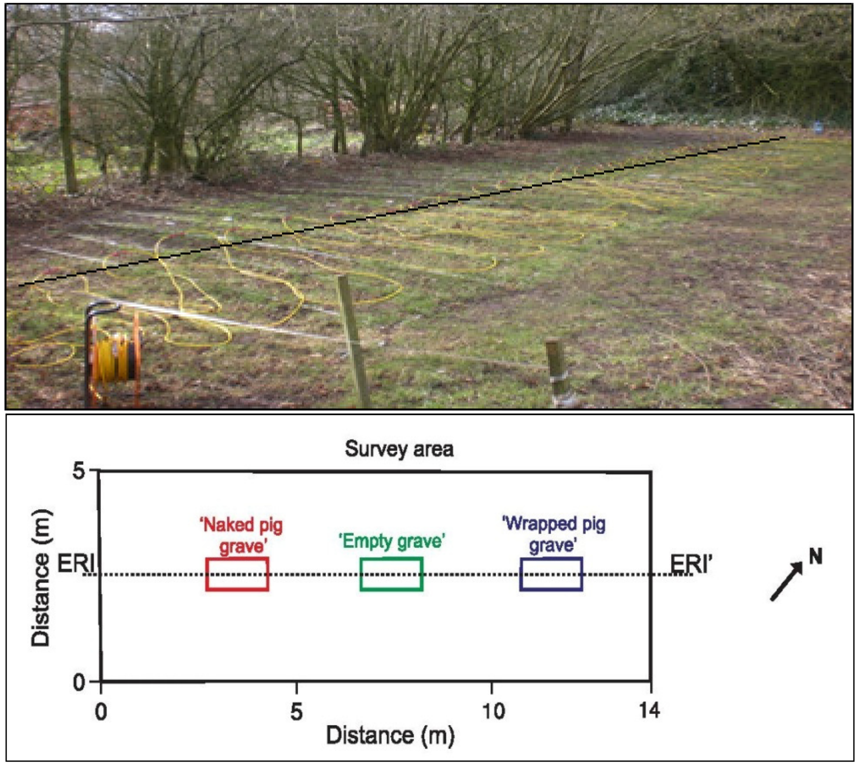


Fig. 3.4: Electrical Resistivity Imaging acquisition scheme and view: . 'Naked pig grave'in red, 'Empty grave' in green, 'Wrapped pig grave' in blue.

For the first survey 3 months after burial, dipole-dipole, Schlumberger and Wenner array configurations were all collected, with the Wenner array configuration deemed optimal at this site. Therefore, Wenner array data were collected for all subsequent ERI surveys.

These data sets were semi-automatically collected by a Campus_TIGRE (Campus International Products Ltd., Dunstable, UK) (Fig. 3.4) system using ImagerPro_2006 data acquisition software (Media Cybernetics Inc., Bethesda, MD). It automatically calculates the apparent resistivity related to each electrodes spacing.

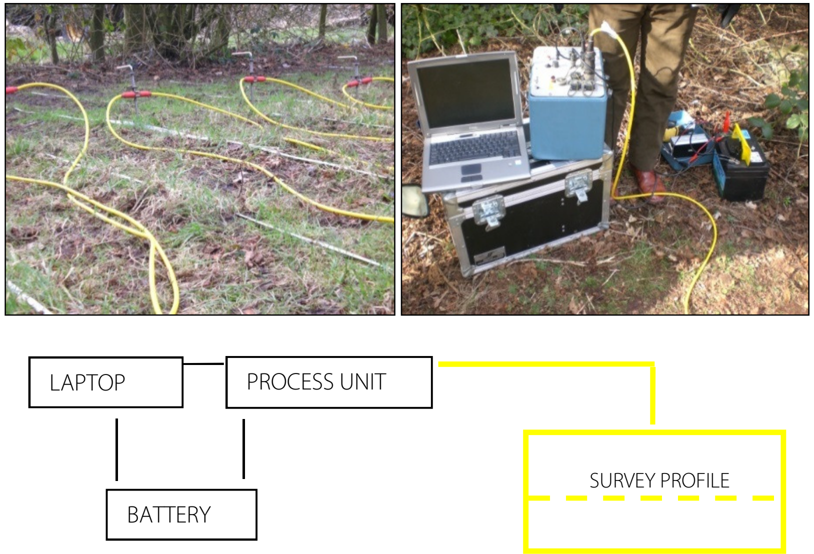


Fig. 3.5: Electrical Resistivity Imaging equipment and scheme: electrodes, Process unit, laptop (software) and batteries.

Ten "n" levels were collected for each survey. The ERI surveys each took ~2 hours to acquire.

3.3.2 Monitoring activity

Survey were done at c. 3-monthly intervals, starting at 3 months after burial (Table 3.2).

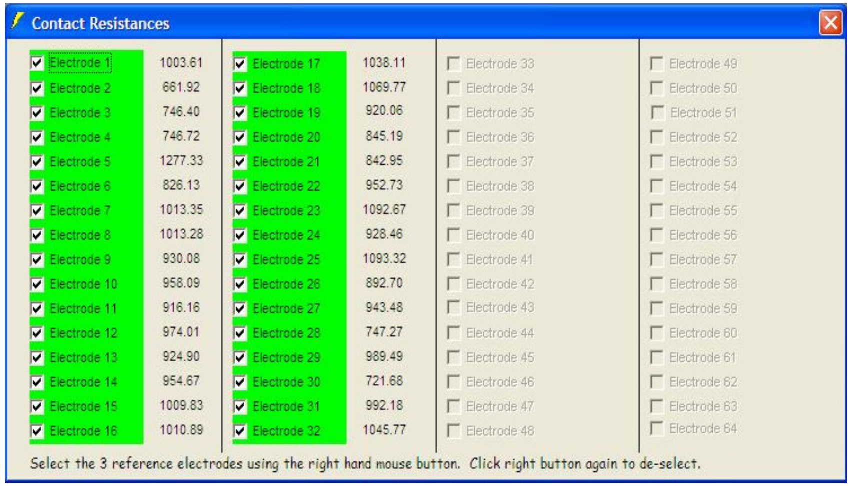
Year	Years after burial	Date	Months after burial
2007	0	-	0
2008	1	07/03	3
		05/06	6
		01/09	9
		04/12	12
2009	2	06/03	15
		20/05	18
		11/08	21
		13/11	24
2010	3	20/04	27
		28/06	30
		28/09	33
		03/12	36
2011	4	15/03	39
		22/06	42
		09/09	45
		06/12	48
2012	5	12/03	51
		03/07	54
		10/09	57
		07/12	60
2013	6	12/03	63

Tab. 3.2 : Electrical Resistivity Imaging monitoring activity

3.3.3 Relevant aspects about data collection

Since depth-sounding involves expansion about a centre point, the instruments generally stay in one place. Instrument portability is therefore less important than in profiling.

Erroneous readings are usually due to poor ground contact. Since the acquisition of the entire profile requires waiting for about two hours, before starting the software (Fig. 3.5) allows the user to check good contact of the electrodes, ensuring that the contact resistance is comparable on each electrode of the array. If it's not, the software alerts the user.



Contact Resistances

☑ Electrode 1	1003.61	☑ Electrode 17	1038.11	☐ Electrode 33	☐ Electrode 49
☑ Electrode 2	661.92	☑ Electrode 18	1069.77	☐ Electrode 34	☐ Electrode 50
☑ Electrode 3	746.40	☑ Electrode 19	920.06	☐ Electrode 35	☐ Electrode 51
☑ Electrode 4	746.72	☑ Electrode 20	845.19	☐ Electrode 36	☐ Electrode 52
☑ Electrode 5	1277.33	☑ Electrode 21	842.95	☐ Electrode 37	☐ Electrode 53
☑ Electrode 6	826.13	☑ Electrode 22	952.73	☐ Electrode 38	☐ Electrode 54
☑ Electrode 7	1013.35	☑ Electrode 23	1092.67	☐ Electrode 39	☐ Electrode 55
☑ Electrode 8	1013.28	☑ Electrode 24	928.46	☐ Electrode 40	☐ Electrode 56
☑ Electrode 9	930.08	☑ Electrode 25	1093.32	☐ Electrode 41	☐ Electrode 57
☑ Electrode 10	958.09	☑ Electrode 26	892.70	☐ Electrode 42	☐ Electrode 58
☑ Electrode 11	916.16	☑ Electrode 27	943.48	☐ Electrode 43	☐ Electrode 59
☑ Electrode 12	974.01	☑ Electrode 28	747.27	☐ Electrode 44	☐ Electrode 60
☑ Electrode 13	924.90	☑ Electrode 29	989.49	☐ Electrode 45	☐ Electrode 61
☑ Electrode 14	954.67	☑ Electrode 30	721.68	☐ Electrode 46	☐ Electrode 62
☑ Electrode 15	1009.83	☑ Electrode 31	992.18	☐ Electrode 47	☐ Electrode 63
☑ Electrode 16	1010.89	☑ Electrode 32	1045.77	☐ Electrode 48	☐ Electrode 64

Select the 3 reference electrodes using the right hand mouse button. Click right button again to de-select.

Fig. 3.6: ImagerPro_ 2006 data acquisition software, contact resistance check

If the resistance of the current becomes anomalously high, the applied current may fall to zero and the measurements will fail. High contact resistances are particularly common when the surface material into which the electrodes are implanted consists of dry sand, boulders, gravel, frozen ground, ice or laterite. The method commonly used to solve the problem is to wet the current electrodes with water or saline solution.

Another issue concerns spacing and imaging resolution. The horizontal resolution is defined by the inter-electrode spacing, and the vertical resolution by half the spacing. Whether the sub-surface features can be resolved at a comparable scale is determined also by the lateral and vertical variations in true resistivity. An electrode spacing of 0.5 m was chosen to obtain a maximum depth of investigation of approximately 2 m, which provides suitable imaging resolutions for graves extents and depth ranges.

Array orientation is often constrained by local conditions, i.e. there may be only one direction in which electrodes can be taken a sufficient distance in a straight line. If there is a choice, an array should be expanded parallel to the probable strike direction, to minimize the effect of non-horizontal bedding. It is generally desirable to carry out a second, orthogonal expansion to check for directional effects.

An example of this effect is provided by the Wenner array resistivity profile from a physical modelling experiment (Fig. 3.6, (9)). The data were collected over a thin, horizontal sheet, the size and position of which relative to the measurements location is indicated by the black rectangle, labelled 'H'. Two horizontal resistivity profiles are shown, line (labelled '1') was collected with the electrodes parallel to the plane of the page, whilst the other profile ('2') was collected with electrodes perpendicular to the plane of the page.

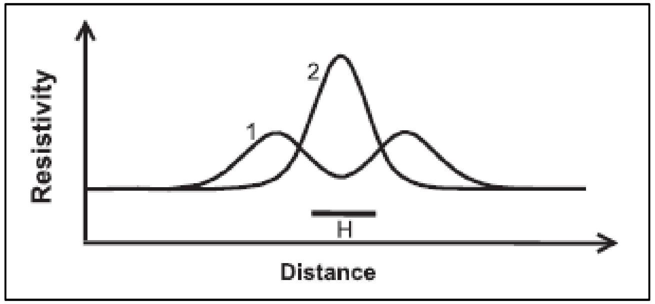


Fig. 3.7: Wenner array resistivity profile from a physical modeling experiment (9)

CHAPTER 4

DATA PROCESSING

4.1 CONSTANT OFFSET RESISTANCE SURVEY

4.1.1Purpose

The purpose of the processing sequence is to highlight the presence of anomalies in resistivity mapping, trying to remove the influences on the surrounding environment.

Low resistivity anomalies with respect to background values would be expected over clandestine burials (15) due to increased soil porosity (caused by the digging) and the presence of burial fluids with their associated increase in conductivity. This change is influenced by some factors:

- size of target,
- area of disturbance,
- depth of burial,
- body wrapping,
- state of decomposition,
- nature of substrates,
- climate,
- ground saturation.

However, most survey areas have natural trends that reflect local geology or other material variation, or moisture content variations related to seasonal changes should be removed from the data to clearly image a 'target'. This is called a *site trend*, and should be removed from datasets.

4.1.2 Software

Resistivity survey data were processed using the Generic Mapping Tools software (21). The Generic Mapping Tools (GMT) are an open-source collection of computer software tools for processing and displaying xy and xyz datasets, including rasterisation, filtering and other image processing operations, and various kinds of map projections.

It was primarily developed to aid the geophysics data processing, using raw *.xyz data to produce processed map-view images of datasets. It uses text scripts as data input. The logical operation scheme is presented in Fig 4.1.

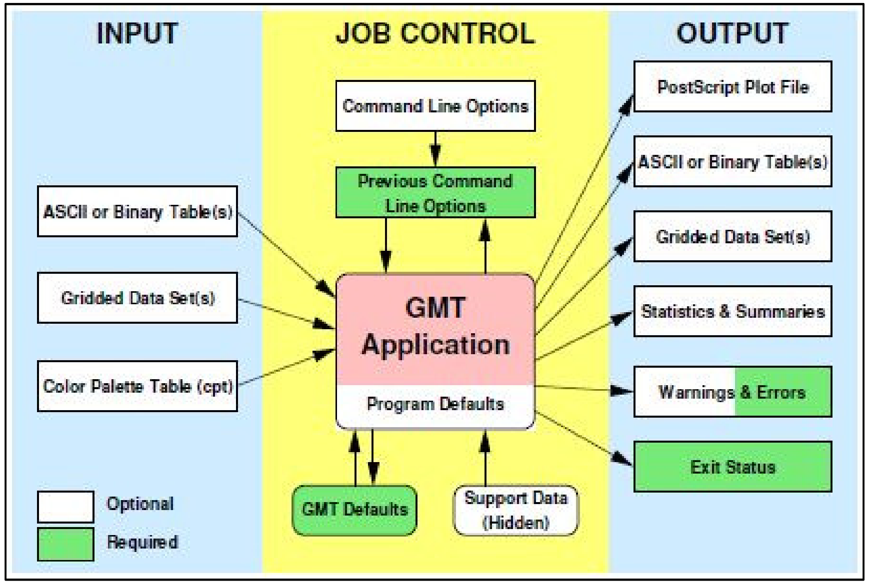


Fig. 4.1: GMT software logical operation (21)

4.1.3 Steps

1. RAW DATA

Each set of acquisition provides a *.xyz file in which, for each position, a value of apparent resistivity is given.

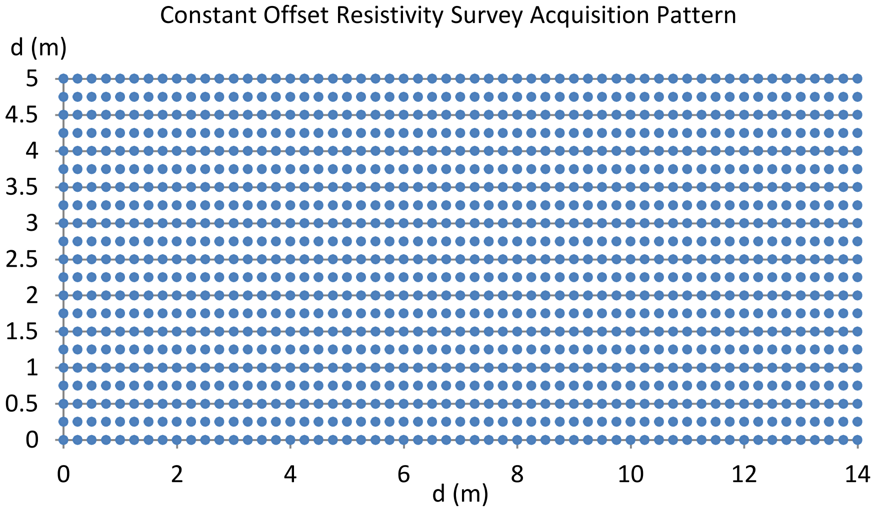


Fig. 4.2:Constant Offset Resistivity Survey Acquisition Pattern: in axes the distance d (m)

2. OUTLIERS REMOVAL

Erroneous readings are usually due to poor ground contact: they result in resistance value clearly overrated with respect to near values. For each dataset, outliers were manually identified and removed.

3. INTERPOLATION

To aid visual interpretation of the data, a surface is created with a minimum curvature gridding algorithm. Each data set was interpolated to a cell size of 0.125 m • 0.125 m, which is the half of the acquisition spacing (0.25 m).

```
surface input.xyz –R0/14/0/5 –I0.125/0.125 –Ginput_res.grd
```

When data are interpolated using a cell size that is smaller than the spacing between data points, if applied to rectangular grids with missing values (which was the case for most of the grids in this study), it can result in spurious resistivity values appearing in the regions with missing values.

4. TREND REMOVAL

Long-wavelength trends were removed from the data to allow smaller, grave-sized features to be more easily identified. Trend removal was achieved by fitting a cubic surface to the gridded data and then subtracting this surface from the data.

```
grdtrend input_res.grd –N10r –Dinput_detrended.grd –Tinput_trend.grd
```

It reads a 2-D grid file and fits a low-order polynomial trend to these data by least-squares. The trend surface is defined by:

m1 + m2*x + m3*y + m4*x*y + m5*x*x + m6*y*y + m7*x*x*x + m8*x*x*y + m9*x*y*y + m10*y*y*y.

The user must specify –Nn model, the number of model parameters to use.

5. NORMALIZATION

To remove the influence of seasonal changes in site conditions, survey data were normalized: the mean of the dataset is subtracted from each data and the results is then divided by its standard deviation.

All processed, normalized data sets then has a zero mean value and standard deviation units, which makes comparisons between different resistivity survey data sets possible. The plotted data reflects how many standard deviations from the average that data lies.

```
grdinfo -L2 input_detrended.grd
grdmath input_detrended.grd 34.65053895 SUB = input_sub.grd
grdmath input_sub.grd 3.45580 DIV = input_std.grd
```

6. EDITING and PLOTTING

An empty basemap frame with optional scale and a colorbar contours were created to aid visualization of data.

```
makecpt -Chaxby -T-3.4558021/3.4558021/0.01 >63months.cpt
psbasemap -R0/14/0/5 -Jx0.25 -Bf1a2:"x axis":/1:"y axis":WeSn -P -K
>63months_plot.ps
grdimage 63months_normalised.grd -R -J -P –C63months.cpt -O -K
>63months_plot.ps
psscale -D6.83/0.75/1.5/0.2 -Bf1a2 –C63months.cpt -O >63months_plot.ps
```

The sequence of the processing phases is summarized in Fig 4.3.

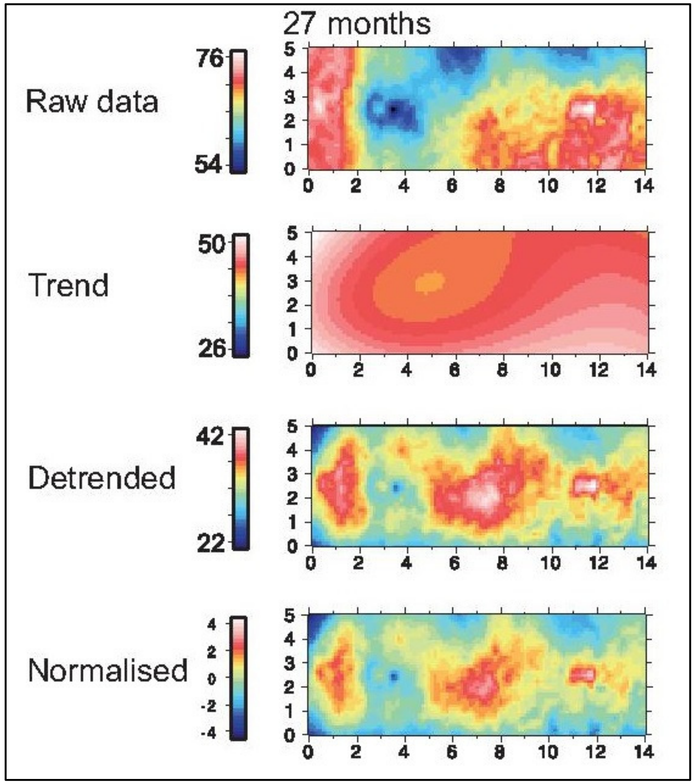


Fig 4.3: Constant Offset Resistivity Survey processing phases for the 27months after burial survey

4.2 ELECTRICAL RESISTIVITY IMAGING – ERI

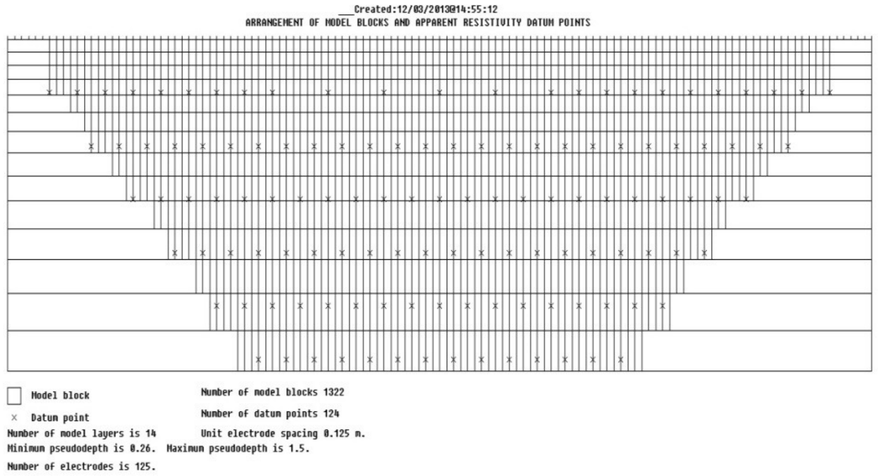
4.2.1Purpose

The purpose of processing ERI raw data is to determine a 2D vertical true resistivity pseudo-section that agrees with actual measurements.

What the probes measure in each point of the vertical pattern is the resistance, then converted into apparent resistivity. Starting from these values a least square algorithm is applied to create a model of apparent resistivities which minimize RMS (Root Mean Square) error. This model is then inverted and a vertical profile of true resistivities is created.

4.2.2 Software

Raw ERI data sets were individually processed and inverted utilizing a least-squares inversion approach using Geotomo_Res2Dinv v.355 software (Geotomo Software, Penang, Malaysia).
Res2Dinv is a computer program that will automatically determine a two-dimensional resistivity model for the subsurface for the data obtained from electrical imaging surveys (Griffiths and Barker 1993).
The 2D model used by the inversion program consists of a number of rectangular blocks: the distribution and size of the blocks is automatically generated by the program using the distribution of the data points as a rough guide.



```
Number of model blocks 1322
Number of datum points 124
Number of model layers is 14        Unit electrode spacing 0.125 m.
Minimum pseudodepth is 0.26.  Maximum pseudodepth is 1.5.
Number of electrodes is 125.
```

Fig. 4.4: Res2Dinv arrangement of model blocks and apparent resistivity datum points

The purpose is to determine the resistivity of the rectangular blocks that will produce an apparent resistivity pseudosection that agrees with the actual measurements. For the Wenner array the thickness of the first layer of blocks is set at 0.5 times the electrode spacing. The thickness of each subsequent deeper layer is normally increased by 10% or 25%. The depth of the bottom row blocks is set to be equal to the equivalent depth of investigation of the data points.

4.2.3 Steps

1. BAD DATA POINT REMOVAL

Remove data points that have resistivity values which are clearly wrong. Such bad data points could be due to the failure of the relays at one of the electrodes, poor electrode contact due to dry soil, or shooting across the cables due to very wet ground conditions.

These bad data points usually have apparent resistivity values that are obviously too large or too small compared to the neighboring data points. The best way to handle them is to drop them so that they do not influence the model obtained. A half-cell spacing was utilized during the inversion process to reduce any near-surface electrical resistivity variations.

The result is that the number of data points decreases while the total number of electrodes doubles. The bottom four "n" levels were removed to avoid potential edge effects.

```
___Created:12/03/2013@14:55:12
Electrode spacing is 0.500.
Wenner array
Total number of datum points is 155.
Position of mid-point of array is given.
155 8.000  5.000    157.3
Minimum electrode location is 0.0.
Minimum electrode spacing is 0.5.
Total number of data levels is 10.
Total number of electrodes is 32.
First electrode is located at 0.000.
Last electrode is located at    15.5.
```

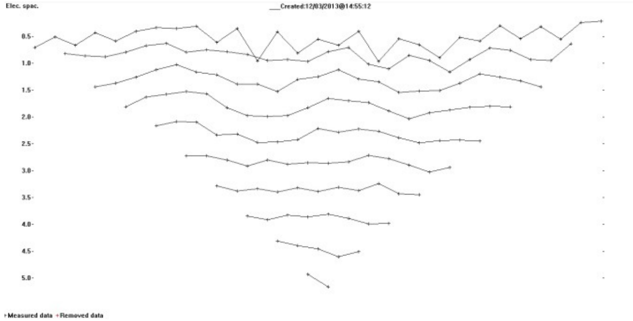


Fig 4.5: Res2Dinv data point pattern before bad data point removal

```
___Created:12/03/2013@14:55:12
Electrode spacing is 0.250.
Wenner array
Total number of datum points is 124.
Position of first electrode in array is given.
124 6.500  3.000    178.9
Minimum electrode location is 0.0.
Minimum electrode spacing is 0.3.
Total number of data levels is 6.
Total number of electrodes is 63.
First electrode is located at 0.000.
Last electrode is located at    15.5.
```

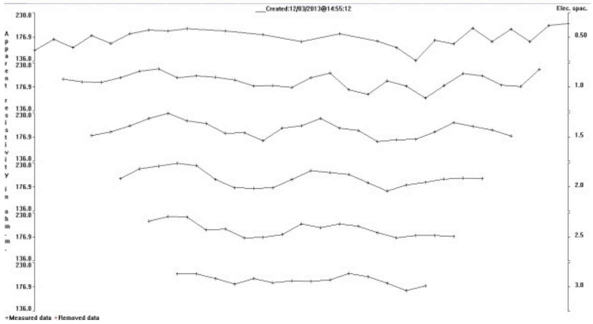
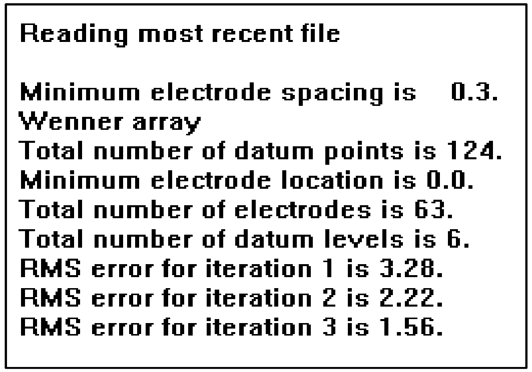


Fig 4.6: Res2Dinv data point pattern after bad data point removal

2. INVERSION

The least squares optimization method basically tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting resistivity of the model blocks. A measure of this difference is given by the root-mean-square (RMS) error. However the model with the lowest RMS error can sometimes show large and unrealistic variations in the model resistivity values and might not be the "best" model from a geological perspective. In general the most prudent approach is to choose the model at the iteration after which the RMS error does not change significantly. This actually occours between the 3rd and the 5th iterations and during processing it was always less than 5%.



```
Reading most recent file

Minimum electrode spacing is    0.3.
Wenner array
Total number of datum points is 124.
Minimum electrode location is 0.0.
Total number of electrodes is 63.
Total number of datum levels is 6.
RMS error for iteration 1 is 3.28.
RMS error for iteration 2 is 2.22.
RMS error for iteration 3 is 1.56.
```

Fig.4.7: Res2Dinv Inversion report

3. VISUALIZATION OF INVERTED RESULTS

The visualization of results comprehends the 'measured apparesent resistivity pseudosection' (the one given as a input), the 'calculated apparent resistivity pseudosection' (the one calculated throughout the true resistivity inverted model) and the 'true Resistivity section' (Fig. 4.8).

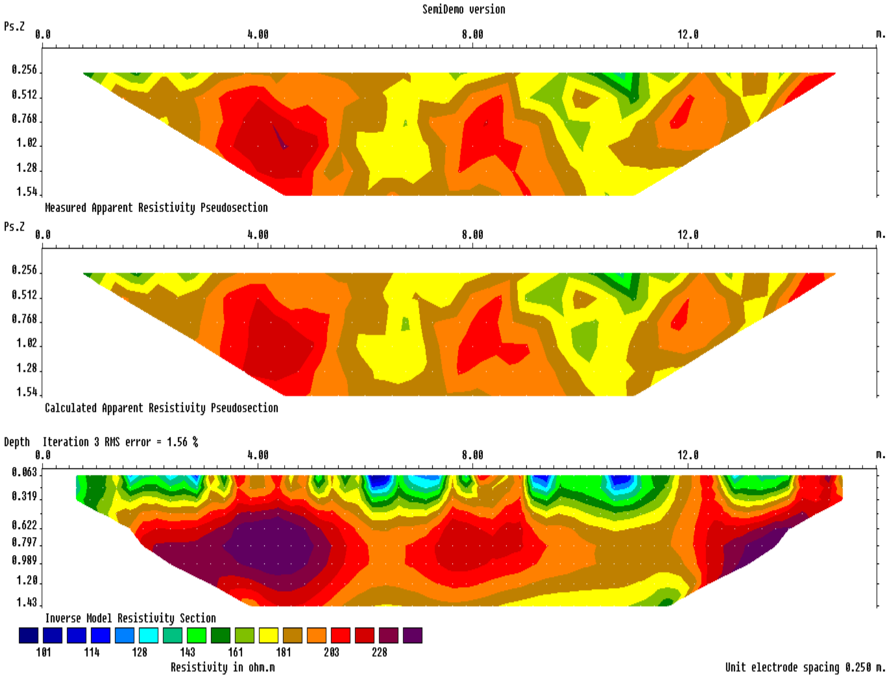


Fig. 4.8: Res2Dinv final result

CHAPTER 5

RESULTS and DISCUSSION

5.1 CONSTANT OFFSET RESISTANCE SURVEY RESULTS

5.1.1 Results

Assuming to work in an active case, so without the need of comparison between periodical surveys, an attempt to plot the results without normalization has been made and each survey has been plotted with its own colorbar contours (Fig. 5.1). The purpose was to assess whether the step of normalization aids the detection of the anomaly. This proved to be true, so the following discussion is based on the normalized results plotted with the same colorbar contours (Fig. 5.2).

The un-normalised values are in terms of Resistance (Ω): in each point they differ from the apparent resistivity values (Ωm) by a multiplicative geometric factor equal to 2π**a**, where **a** is the constant offset between the mobile probes (0.5 meters in this case).

The normalised values are normalized Resistance values (-): they reflect how many standard deviations from the average that data lies.

Values are referred to a depth of investigation of approximately the same as the mobile electrodes separation, so 0.5 meters depth (for explanation see Fig.2.16 page 34).

A Constant Offset Resistance Survey was performed before burial and named 'Control survey' (Fig. 5.1 A, Fig. 5.2 A): it is fundamental for comparisons.

Statistics calculated for the normalization processing step (standard deviation and mean value of each data set) are plotted in time after burial (Fig. 5.3) as well as monthly total rainfalls collected by the nearby meteorological weather station (Fig.5.4) .

Un-normalized Constant Offset Resistance Survey results

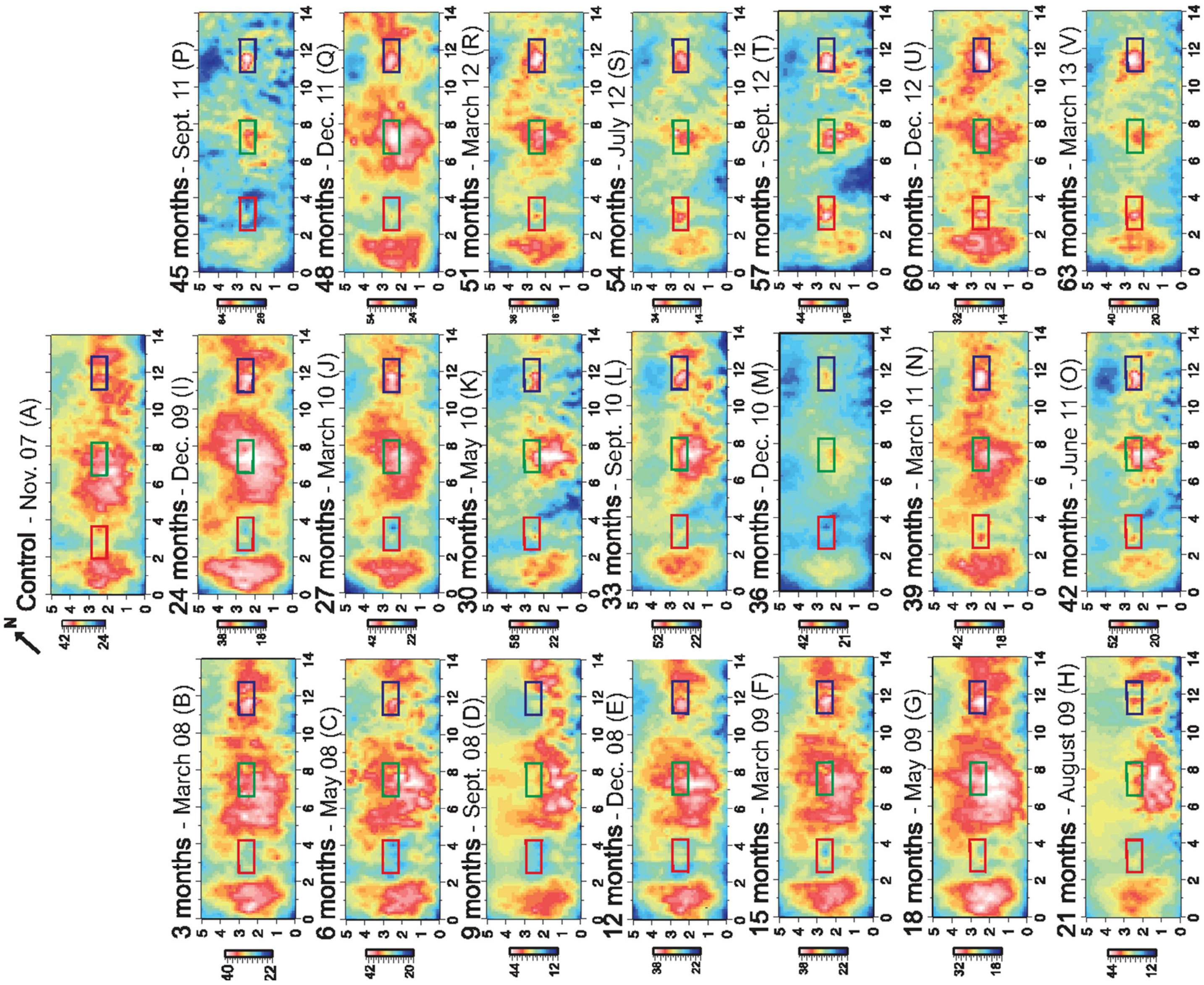


Fig. 5.1: Un-normalized Constant Offset Electrical resistance processed data sets. Each plot shows Resistance values(Ω) using its own colorbar contour. Locations of the targets are marked with colored rectangulars: 'Naked pig grave' location in red, 'Empty grave' in green, 'Wrapped pig grave' in blue. Period of acquisition and months after burial at that time are specified.

Normalized Constant Offset Resistance Survey results

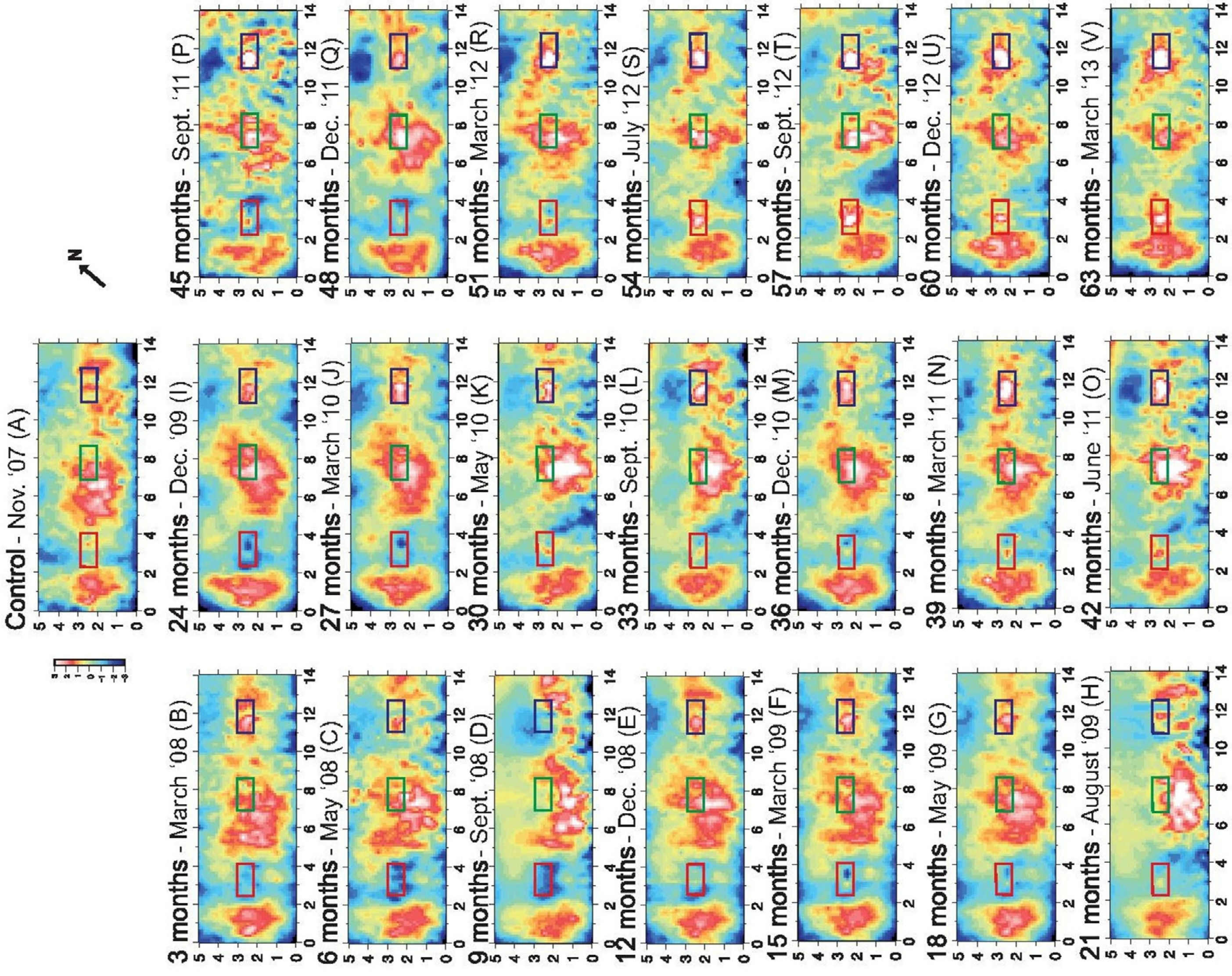
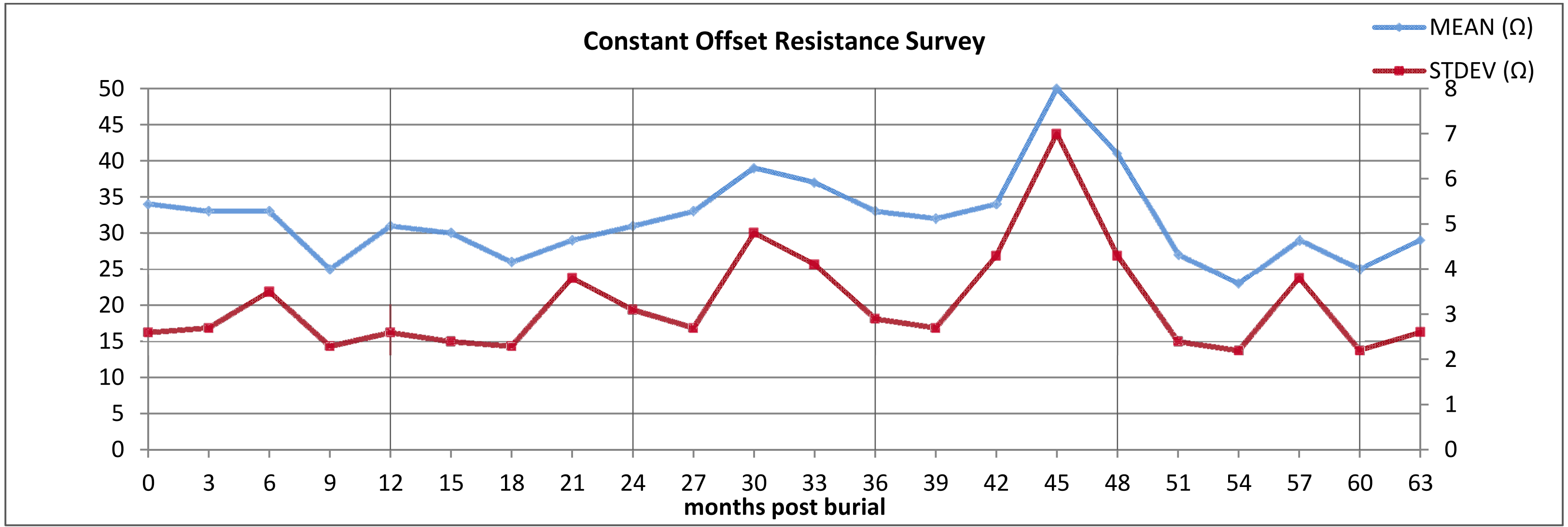
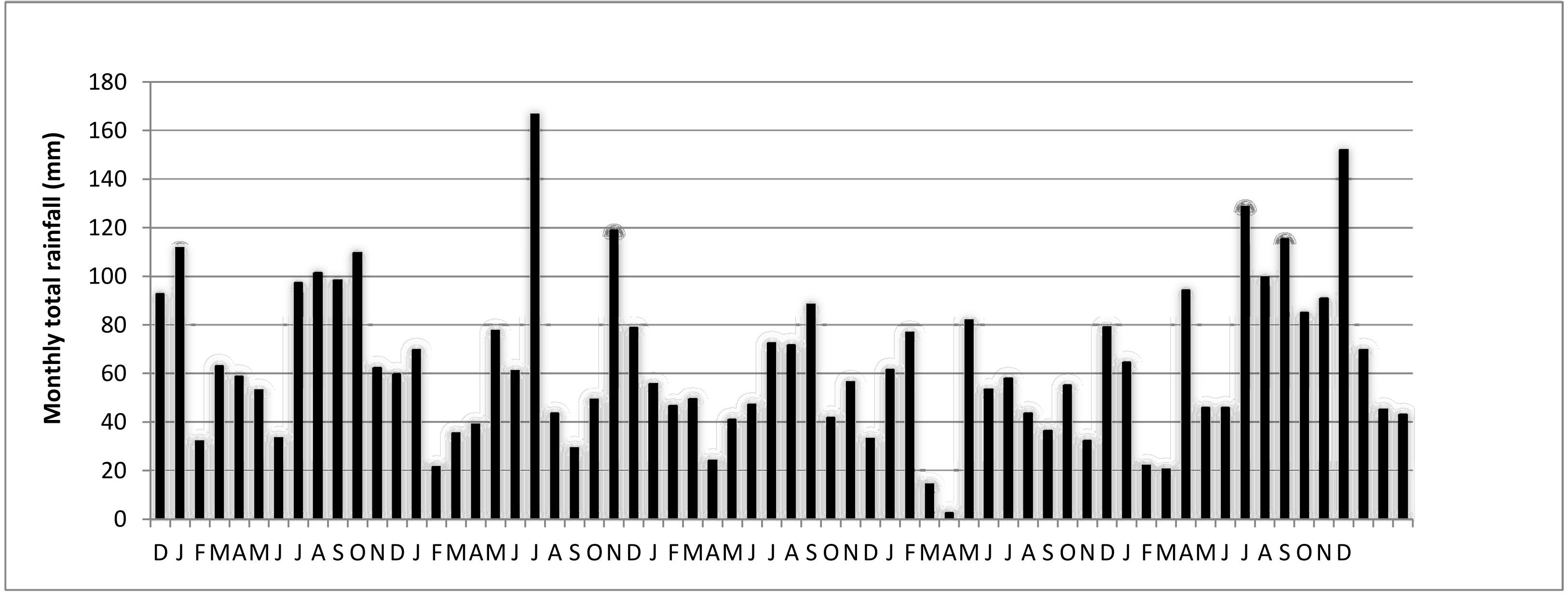


Fig. 5.2: Normalized Constant Offset Electrical resistance processed data sets. Each plot shows Normalized Resistance values(-) using the same colorbar contour. Locations of the targets are marked with colored rectangulars: 'Naked pig grave' location in red, 'Empty grave' in green, 'Wrapped pig grave' in blue. Period of acquisition and months after burial at that time are specified.



Graph 5.1: Constant Offset Resistance Standard Deviation and Mean Value in time after burial



Graph 5.2: Monthly total rainfall data (mm) in time after burial

5.1.2 Discussion

Discussion about results is based on the normalized results plotted with the same colorbar contours (Fig. 5.2) and is conducted analyzing the plotted data sets with respect to possibility to localize an anomaly in correspondence of the known grave location (colored rectangulars) with Constant Offset Resistance Survey. Results are evaluated with respect to intensity and extent of the anomaly.

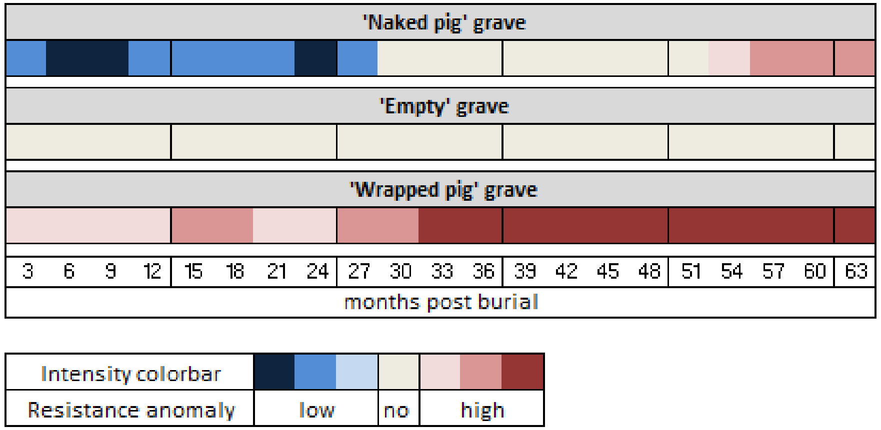


Fig. 5.3: Constant Offset Resistance Survey time-lapse diagrams

The 'Control survey' shows strong anomalies most likely related to the tree root system caused by the trees on the border of the survey area, altering the moisture content of the ground: in fact they adsorb soil water, so the resistance of the soil in their proximity increases (22). This evidence remarks the influence of environmental factors on the survey.

'Naked pig' grave

In the first two years the grave is detectable as a low resistance anomaly. The most likely explanation for this is that the mixing of decomposition fluid with the soil lead to a localized increase in groundwater ion concentrations compared to the background site resistance values.

Cheetham (6) suggests that the release of decomposition fluids into the ground will lower soil resistivity. Pringle et al. (29) carried out regular soil water collection and analysis from the simulated clandestine grave in the same test site via lysimeter: they proved to be significantly elevated conductivity measurements when compared to background values. A temporal rapid increase of the conductivity of burial fluids was observed until one-year post burial, after this values slowly increased until two years (end of that current study period, Fig. 5.4). Jervis et al. (17) conclude that the increase in fluid conductivity within the pig grave observed in the pig grave water conductivity data, would explain the low resistivity anomaly in correspondence with this grave.

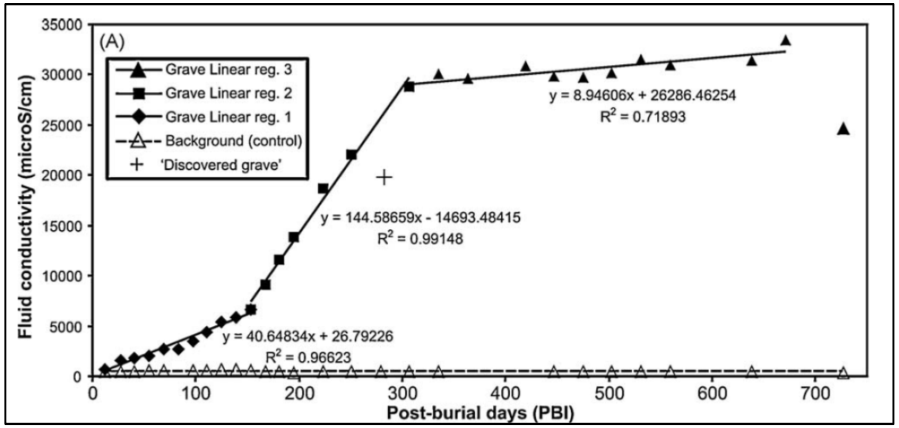


Fig. 5.4: Measured pig leachate (grave) and background soil water fluid conductivity values in time after burial (29)

Although the anomaly varies temporally in both plan view size and relative amplitude compared to background value. The gradual accumulation of conductive decompositional fluid in the porous soils around the cadaver could explain the increase in area and magnitude of the pig grave anomaly in the first 9 months after burial, when the extent of the anomaly is comparable with the extent of the simulated grave created, and the magnitude is maximum.

By then the detectability decreases and the grave is no more detectable as a resistance anomaly until the end of the fourth year. Checking the monthly rainfalls data in the corresponding period (between 30 and 54 months after burial), it's pointed out that there are no picks and there's even a minimum. Moreover total rainfalls in this period (1300 mm) are less than those in the corresponding period of the previous years (1618 mm). This suggests that, in particularly dry weather conditions the grave soil could lose moisture more rapidly and fluids infiltrate together with the soil water in depth, so they would not be identified as an anomaly as the depth would be out of the investigation range(approximately equal to the mobile probes offset)

By the fourth year instead a localized high resistance anomaly increasingly appears. Now the decomposition fluids are widespread into the surrounding soil while the skeleton is localized in the grave. The skeleton is highly resistive with respect to the background soil that contains conductive decomposition fluids and this would lead to a high resistance anomaly.

'Empty' grave

Generally, the disturbed soil in a grave is more porous than the surrounding soil (6,15) because of the digging activity. This increase in porosity would allow the grave soil to have a higher volumetric moisture content, which would lower the resistivity of the grave soil (6,15). Although, in this case the perturbation of the soil porosity induced by the digging is not sufficient to be denoted by this method. Jervis (9) suggests that it is then possible that increases in moisture content in the more porous soil of a grave only occur under a certain site specific conditions, such as in certain soil types or under certain environmental conditions. This evidence confirms that, overall, the presence of a buried cadaver enhances the detectability of the filled grave.

'Wrapped pig' grave

Till one year from burial the grave results being weakly detectable as a high resistance anomaly. In this period the decay activity should be maximum but the tarpaulin wrapping around the cadaver acts as an inhibitor for decomposition by microorganisms and as a barrier from fluids to spread in the soil because of its non-permeability. Pringle et al (28) suggest that the weak high anomaly is reasonably due to the wrapping acting like a barrier to the flow of electrical current in the ground.

From year one onward it becomes increasingly detectable as a high resistance anomaly till two years and half, when it's at the maximum detectability: this could be explained as a consequence of the leakage of decomposition fluids into the surrounding soil. The background resistance values decrease so the presence of the tarpaulin wrapping constitutes a strong anomaly with respect to the background because it acts as barrier to the higher flow of electrical current in the surrounding soil.

5.2 ELECTRICAL RESISTIVITY IMAGING – ERI RESULTS

5.2.1 Results

Assuming to work in an active case, so without the need of comparison between periodical surveys, results were plotted each with its own colorbar contours, those given by default by Res2Dinv software which uses logarithmic contour intervals (Fig. 5.6).

In a monitoring outlook, results were also potted all with the same colorbar contours, a user-defined one, chosen by a statistical data description (Fig. 5.7). This visualization aids the evaluation of the anomalies evolution.

The results are true-resistivity (Ωm) pseudo-sections so conclusions on values can be inferred. No ERI 'Control Survey' is available.

Data sets statistics (standard deviation and mean value of each data set) were calculated and plotted in time after burial, as well as monthly total rainfalls collected by the nearby meteorological weather station (Fig. 5.8 and Fig. 5.9).

Resistance anomalies which differ from simulated graves in the near surface soils present in many of the time-lapse profiles are related to tree-root activity; during spring and summer highly conductive tree roots become active and grow (particularly in soil areas of reduced density or increased porosity such as that of the empty grave) to exploit surface water resources (24).

ERI Survey Results plotted with Different contours

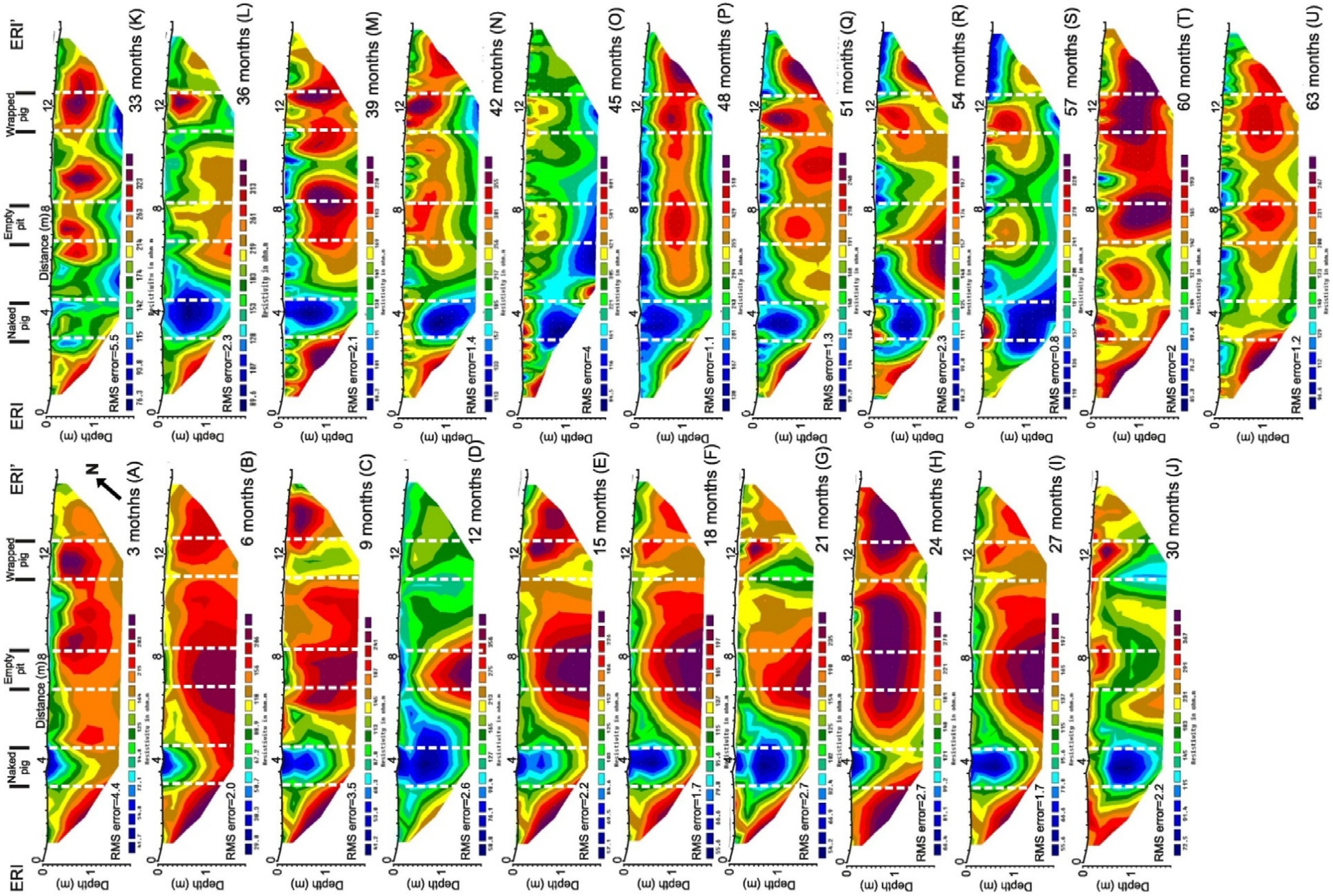


Fig.5.5: Individually inverted 2D Electrical Resistivity Imaging profiles , each plotted with its own default colorbar; Inversion RMS is indicated; locations of 'Naked pig', 'Empty', 'Wrapped pig' graves are indicated by dashed white lines. See Fig. 3.3 to locate the ERI-ERI' survey line.

ERI Survey Results plotted with Same contours

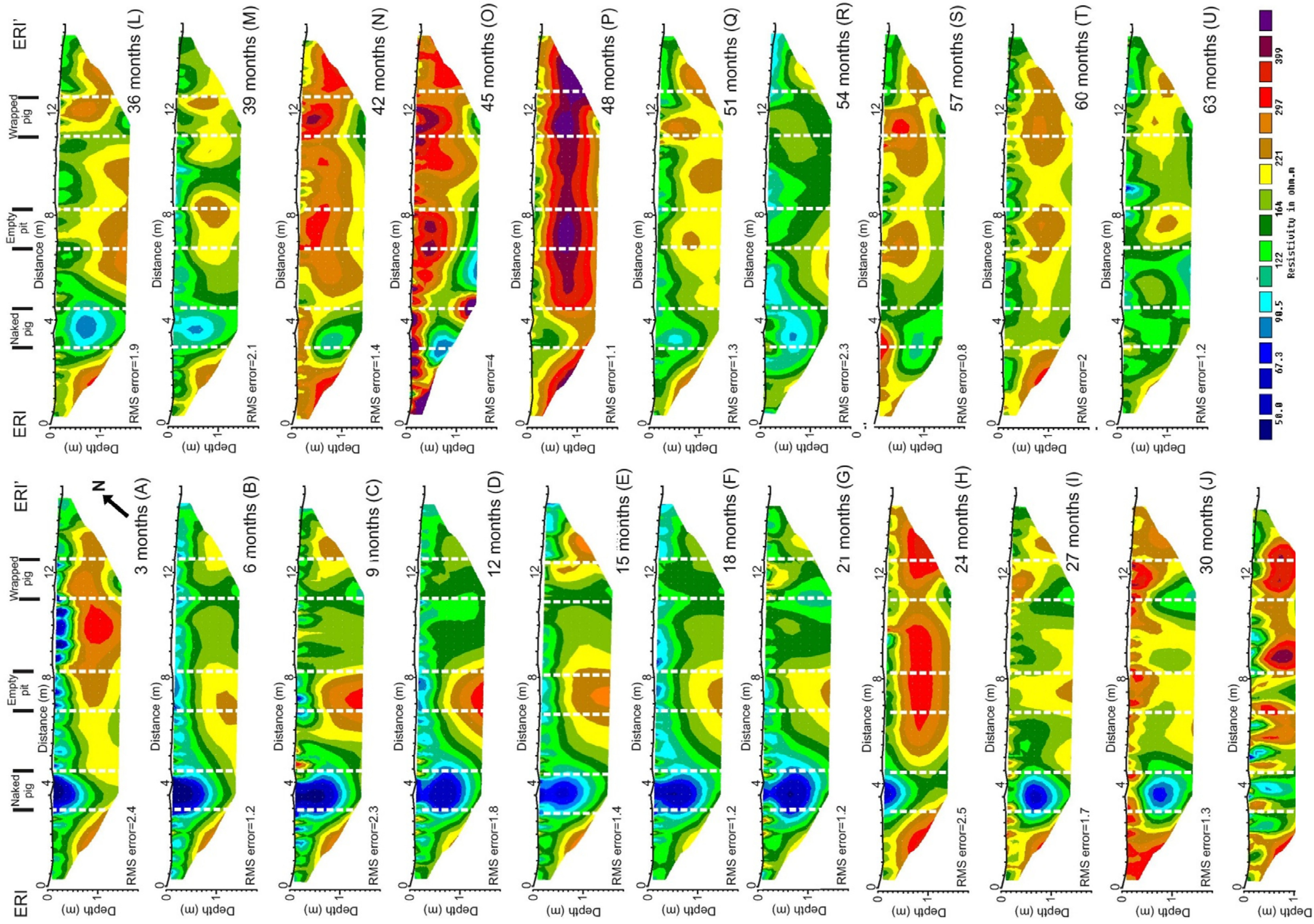
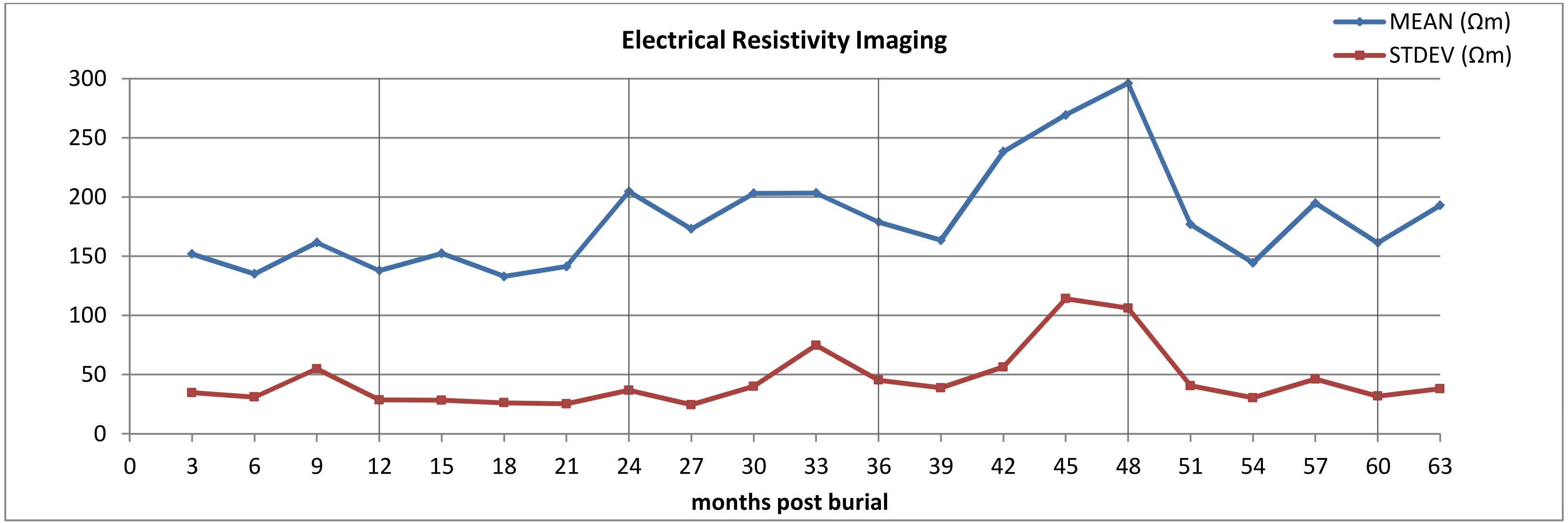
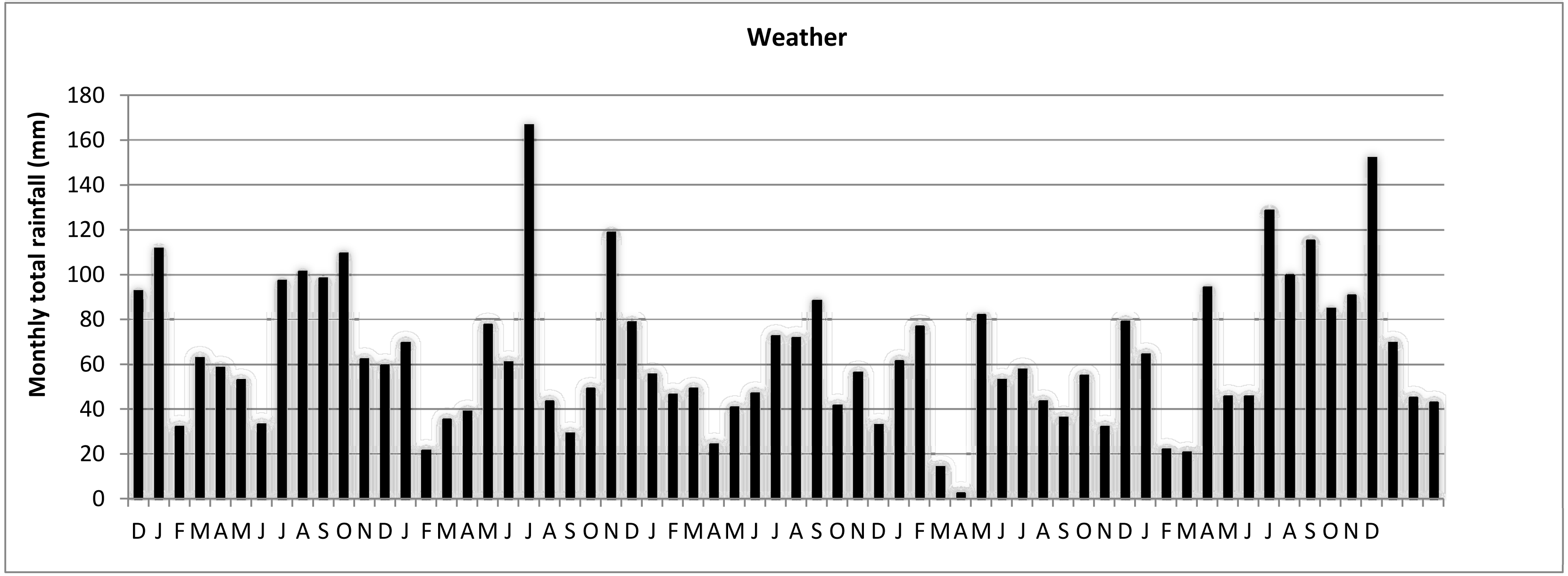


Fig.5.6: Individually inverted 2D Electrical Resistivity Imaging profiles , all plotted with the same user- defined colorbar; Inversion RMS is indicated; locations of 'Naked pig', 'Empty', 'Wrapped pig' graves are indicated by dashed white lines. See Fig. 3.3 to locate the ERI-ERI' survey line.

Statistics and weather data



Graph 5.3: Electrical Resistivity Imaging Standard Deviation and Mean Value.



Graph 5.4: Monthly total rainfall data (mm)

5.2.2 Discussion

The difference between the two visualizations of the same information strongly influences the discussion: it's clear that if an anomaly results of high magnitude (not high resistivity!) when plotted with its own default colorbar contours, this may not be true when plotted with the same colorbar contours chosen on all data sets available by monitoring activity. Generally the visualization with default colorbar contours aids the detectability of the graves, while the one with the same colorbar contours shows the evolution of the anomalies in time after burial in a more effective way.

An unambiguous method to analyze results is to ignore colorbar contours and consider the real true resistivity values in correspondence of the grave position in time after burial.

Time-lapse diagrams are evaluated analyzing the plotted data sets with respect to possibility to localize an anomaly in correspondence of the known grave location (white dotted lines) during active cases (so with the default colorbar contours) and with respect to the magnitude and the extent of the anomaly.

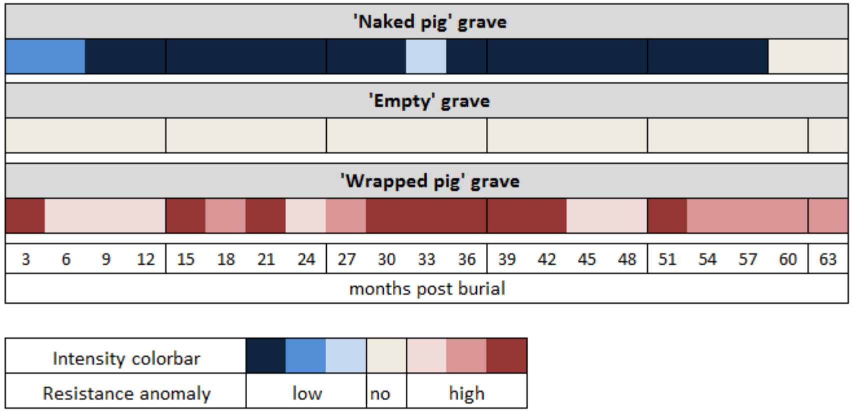


Fig. 5.7: Electrical Resistivity Imaging time-lapse diagrams

'Naked pig' grave

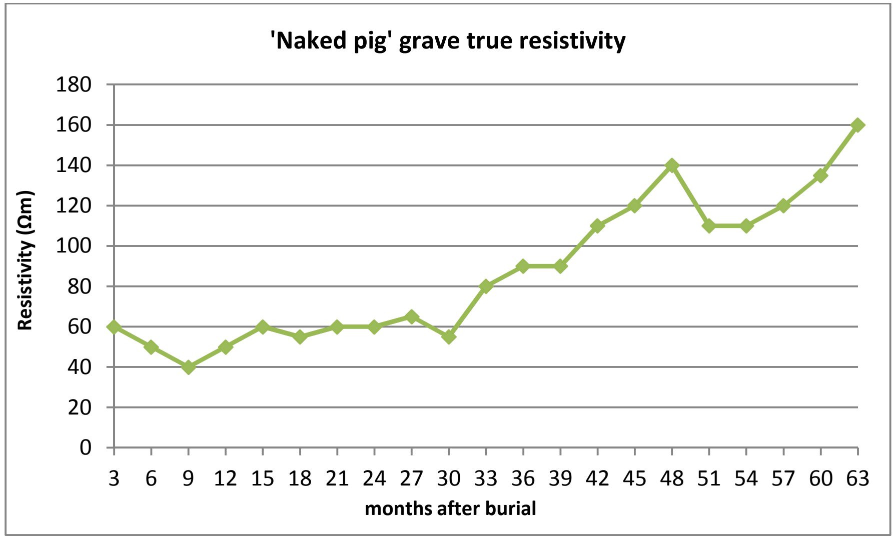
It is identified by a low resistivity anomaly with respect to the background values. Within 6 months after burial the extent of the low resistivity anomaly reflects the dimension in depth of the buried body (the excavated graves is 0.6 meters deep, Fig. 5.6 A,B). Then decomposition fluid starts to be released in the soil so the depth extent of the anomaly doubles in the following three months and triples as well (Fig. 5.6 C-I).

From two years and half onward the low resistivity anomaly is mostly caused by the plume of these fluids into the soil. Spatially the decreases in resistivity are most prominent directly below the cadavers and exhibit a downward shift over time, which is highly indicative of the fluid flow associated with decompositional leachate plumes (Fig. 5.6 J).

The ERI time-lapse profiles plotted with the same colorbar contours (Fig. 5.7) clearly show the evolution in magnitude of the 'Naked pig' grave anomaly, remarking that even if results are generally high when plotted with different colorbar contours, it is instead becoming increasingly smaller in magnitude (i.e. higher resistivity) over time. They show that by 1 year after burial onward the magnitude of the low resistivity anomaly decreases.

The resistivity values in correspondence with the plume are plotted in the following graph: during the first year after burial the resistivity is ~ 50 Ωm, during the second year after burial it is ~ 60 Ωm, and it increases to ~ 70 Ωm in the third year. By the fourth year values increase in a higher but less stable way till the maximum value of ~160 Ωm at the sixth year after burial.

This evolution reflects the drying of the initially fluid-rich cadavers over time. The behavior by the fourth year after burial may reflects the influence of the higher resistivity associated with the skeletal remains of the cadavers.



Graph 5.5: 'Naked Pig' grave true resistivity values in time after burial

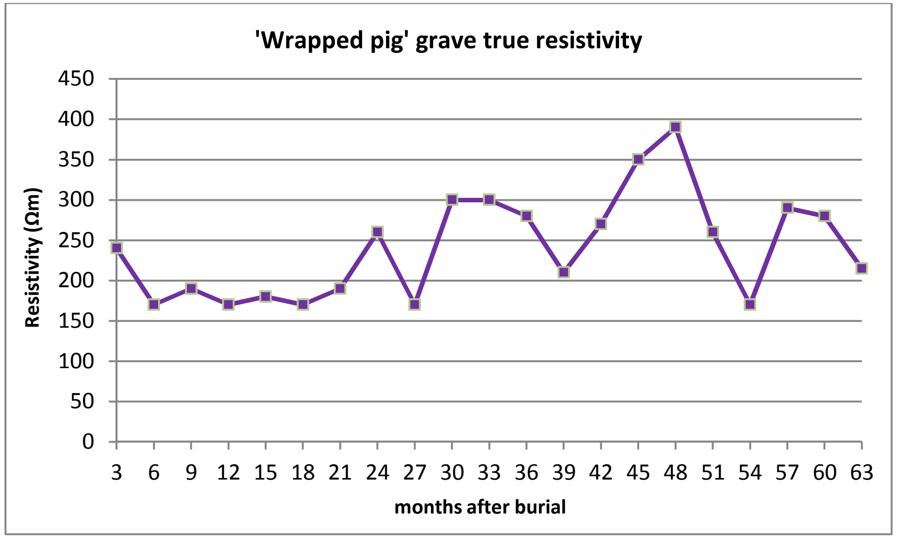
'Empty' grave

Generally, it is thought that the disturbed soil in a grave is more porous than the surrounding soil (6,15). This increase in porosity would allow the grave soil to have a higher volumetric moisture content, which would lower the resistivity of the grave soil (6,15).
Although, in this case the perturbation of the soil porosity induced by the digging is not sufficient to be denoted by this method as well as in Constant Offset Resistance Survey. It is then possible that increases in moisture content in the more porous soil of a grave only occur under a certain site specific conditions, such as in certain soil types or under certain environmental conditions.
However this suggests that, overall, the presence of a buried cadaver enhances the detectability of the filled grave.

'Wrapped pig' grave

The 'Wrapped pig' grave anomaly is not always clearly detectable in ERI profiles. It is in general a high resistivity anomaly, which is consistent with Constant Offset Resistance surveys. Although its magnitude, its location and its extent strongly vary in time as showed by the time-lapse diagrams in Fig. 5.10. The ERI time-lapse profiles plotted with the same colorbar contours (Fig. 5.7) also do not show it effectively.

The initial weak high anomaly is reasonably due to the wrapping acting like a barrier to the flow of electrical current in the ground (28). By the second year after burial it becomes increasingly detectable as a high resistance anomaly till two years and half, when it's at the maximum detectability: this could be explained as a consequence of the leakage of decomposition fluids out of the wrapping and into the surrounding soil. The background resistance values decrease so the presence of the wrapping material constitutes a strong anomaly.



Graph 5.6: 'Wrapped Pig' grave true resistivity values in time after burial

The behavior of the 'Wrapped pig' grave true resistivity values in graph 5.6 reflect the time lapse diagrams strengthen the hypothesis that in the period untill 2 years after burial the tarpaulin wrapped around the cadaver acted as an inhibitor for decomposition by microorganisms and as a barrier from fluids to spread in the soil because of its non-permeability.

CHAPTER 6

CONCLUSIONS

6.1 SUMMARY OF RESULTS

Constant Offset Resistivity Survey and Electrical Resistivity Imaging investigate the same physical property of the ground, by two different points of view: a horizontal map and a vertical profile.

The summary diagram in Fig. 5.8 should be read keeping in mind that evaluations are made in terms of possibility to localize an anomaly in correspondence of the known grave location as a consequence of its presence, referred to each single method and not in comparison. The aim is to gain a better understanding of how clandestine graves can be detected by resistivity surveys in terms of:

- type,
- extent,
- temporal horizon

of modifications of the physical properties of the target and the site induced by the time elapsed since the burial, known as anomalies.

The type of response (high/low anomaly) induced by the presence of the body is the same in both methods because the physical property investigated is identical, although the magnitudes of detectability vary.

Results suggest that the presence of the concealed body itself (and its remains) seems to influence mainly the map view, while the decompositional fluids generated by the body decay mainly influence the vertical section. The reason is mainly related to the nature of the technique of investigation: to asses a standard detection tool is important to be aware of this and to understand the consequences. It is good practice to map search areas and also to carry out some form of depth sounding in order to evaluate what lateral changes have a strong vertical component. The problem is defining from what depth the variations are coming: the plan views are referred to a depth comparable with the mobile probes spacing (0.5 m) and is highly sensitive to horizontal changes, while ERI techniques leads to a higher depth of investigation with a high vertical resolution.

The following summary diagram helps to point out this conclusion.

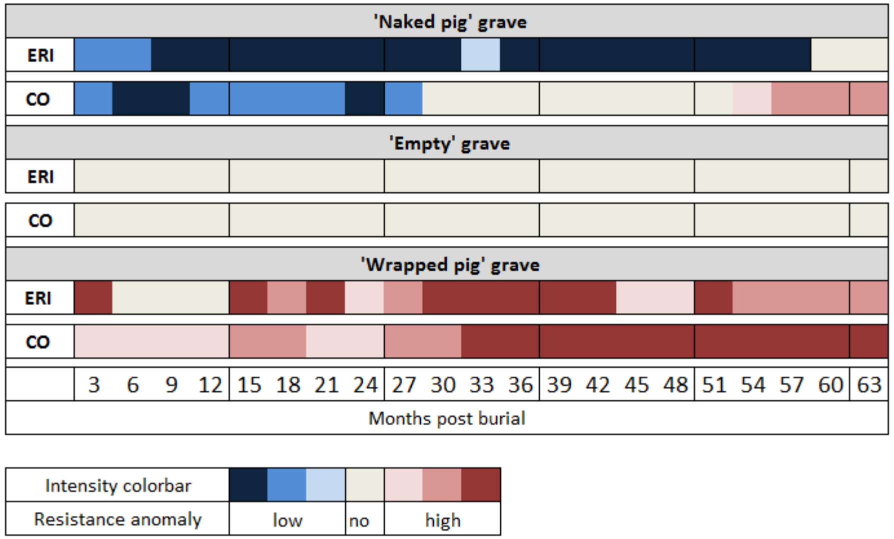


Fig. 5.8: Time-lapse summary diagrams: ERI is for 'Electric Resistivity Imaging', CO is for 'Constant Offset Resistance Survey'.

In case of naked pig grave the ERI (where decompositional fluids are free to spread into the surrounding soil) response is stronger and more stable in time, while in case of wrapped pig grave, where the wrapping is a barrier to the spread, the ERI response is much more instable in time.

Moreover the Constant Offset Resistance technique in case of 'Naked pig' grave after four years and a half gets influenced by the high resistivity remains of the pig (skeleton), while the ERI method does not show this behavior. This characteristic is although very misleading because it compromises the capability of detection. It is therefore fundamental to point out the time and the duration of the anomaly 'turning phase'.

In both cases the 'Empty grave' was not detected as an anomaly: the results presented here suggest that disturbed soil cannot always be detected with resistivity surveys. It is then possible that increases in moisture content in the more porous soil of a grave only occur under a certain site specific conditions, such as in certain soil types or under certain environmental conditions. However this suggests that, overall, the presence of a buried cadaver enhances the detectability of the filled grave.

Evidences of the environmental influences on these survey methods has been found on data statistics.

Standard deviation values have a cyclical behavior: peaks are in correspondence of periods after relatively poor rainfalls so when the moisture content of the ground is reduced with respect other periods of the year. Mean values are also affected by this cyclical variation, as it reflects the high resistivity site trend caused by the diminished water content.
During these periods the information is more "noisy" because some areas of soil dry quicker than others, and this effect can "mask" the targets.

In both methods the existing tree root system in the test site strongly influences the background values they cause some areas of soil dry quicker than others. This could cause anomalies in the resistivity survey data due to variations in the soil moisture content at the study site. It is important to be aware of this when surveying for active cases, as stated in the Geophysical Techniques review (page 15).

Results are in general consistent with published control studies but it should be remarked that this is the longest monitoring activity on simulated clandestine burials.

6.2 IMPLICATIONS

The geophysical monitoring survey results over the simulated clandestine burials shown in this thesis should be used as a reference to allow comparison of data collected by forensic search investigators looking for similar clandestine burials of murder victims. Its long temporal horizon allows to comprehend the consequences of the decay on the detectability of the grave with electrical methods. If the time since burial is approximately known, the grave response can be predicted and targeted.

In active cases, of the two basic modes of resistivity surveying, constant offset horizontal mapping is most commonly used for detecting graves (e.g. 15,16), and ERI is occasionally used (25; 26) because it is significantly slower to cover large areas than fixed offset configuration electrical survey. However, ERI is more useful for determining whether a grave is present at a specific location. As such, ERI can be used to investigate anomalous areas identified through other search methods (26), as it has the added advantage of providing information on vertical, as well as horizontal, variations in resistivity.

Resistivity can be a viable alternative to GPR surveys, particularly if the soil clay content is high or there are significant other non-target objects within the near-surface.

In addition to grave-related factors, some environmental factors affect the ability of resistivity surveys to detect graves:

- the cyclical behavior over seasons of the standard deviation makes it possible to suggest that at some times conditions may be better for detecting graves with resistivity surveys than other times. It can be inferred that resistivity survey is preferable to be collected during winter to mid spring months (when the soil moisture budget is positive) to have the best chance to detect a clandestine burial using resistivity methods. Otherwise, if it is necessary to commence a search immediately during periods when the soil moisture budget is negative, it may be best to use other search methods. Subsequently, resistivity surveys could be used once the soil moisture budget becomes positive if other search methods fail.

- during the initial study of the site potential geophysical disturbances such as boundaries or trees and their related root system should be identified and their contribute to results should be predicted.

6.3 STUDY LIMITATIONS

The limitations are strictly connected to the hypotheses assumed while creating the test site, referring to soil type and grave morphology. Moreover, these recommendations are only relevant to grave-related anomalies that are caused by increased soil-water conductivity as a result of the presence of decomposition products in the ground. Hence, these recommendations may not be relevant in situations when resistivity surveys are known to be able to detect disturbed soil.

Some factors, such as the approximate weight of the cadaver at the time of burial may be known in advance. Other factors, such as whether the cadaver is in some form of wrapping or a container may not be known in advance. This could be a disadvantage, as if the exact contents of the grave are not known, then it will not be possible to predict the likely resistivity response of the grave.

6.4 FURTHER WORK

Resistivity surveys have the potential to be a useful method for locating clandestine graves. Perhaps the most limiting factor is the lack of research on the use of resistivity surveys for locating graves, especially compared to other search methods, such as GPR. Hence, further research is required before resistivity surveys could be routinely used in the search for graves with an appropriate level of confidence.

The study site will be continued to be monitored to discover at what time period after burial will geophysical surveys not be able to determine the location of a clandestine burial and also when "grave soil" conductivity values will either return to background levels or reach equilibrium.

This experimental methodology should be repeated in other, contrasting soil types, to determine whether soil type is a major factor in the ability of forensic geophysical surveys to successfully locate a clandestine burial. As an example, researchers at the TRACES facility at the University of Central Lancashire in Preston, U.K., are acquiring monthly conductivity measurements of a pig cadaver buried at the same burial depth (0.5 m bgl) in a peat soil to compare with this study results.

If data from a controlled experiment that represents a similar scenario to a given case are available, such data should be used to generate appropriate thresholds for identifying and guiding the interpretation of suitable anomalies.

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