Reference: Moffat. I., 2015, *Locating Graves with Geophysics*, in Sarris, A., (ed) Best Practices of GeoInformatic Technologies for the Mapping of Archaeolandscapes, Archaeopress, Oxford, 45-53.

Title: Locating Graves with Geophysics

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The detection and mapping of unmarked graves is a significant focus of many archaeological and forensic investigations however traditional methods such as probing, forensic botany, cadaver dogs or dowsing are often ineffective, slow to cover large areas or excessively invasive. Geophysics offers an appealing alternative suitable for the rapid non invasive investigation of large areas. Unfortunately graves are a challenging target with no diagnostic geophysical response and so the use of a rigorous application-specific methodology is essential for a successful outcome. The most important inclusions in a successful survey methodology include ultrahigh density data, the use of multiple geophysical techniques to validate results based on several physical properties, excellent quality positioning and intensive site recording. Regardless of the methodology applied, geophysics should not be considered a panacea for locating all graves on all sites but should be used as an integral part of a comprehensive survey strategy.

Introduction

‘Thou know’st ‘tis common; all that lives must die, Passing through nature to eternity.’
(Hamlet, Act 1, scene 2, line 72)

The universality of death provides a tangible connection with the past making graves an important, sizeable and evocative component of the archaeological record (Gowland and Knusel 2009, Pearson 1999, Tarlow and Stutz 2013). Graves contain material culture, skeletal evidence of diet and disease and even the act of interring a body has significant implications for the development of behavioral modernity (Pettitt 2010). Murder is, fortunately, a much less universal human experience however losing a loved one in this fashion leads to prolonged and intense trauma for the directly bereaved (Rynearson 1994) and distress in the immediate community and society in general (Morrall 2006). In many cases, successfully locating a

clandestine grave may provide closure to the victim's loved ones and facilitate the prosecution of the murderer.

Despite the importance of locating these features, current methodologies for the detection of unmarked graves (summarized by Killam 1990) remain limited and ineffective due to their small size, subterranean position, lack of surface expression and the often ephemeral nature of their markings. Current methodologies can be effective in some situations, but commonly struggle to cover large areas and deal with burials where the flesh has completely decomposed, as is the case in most archaeological investigations. This difficulty has led to extensive research into the geophysical detection of burials for forensic and archaeological investigations which has accumulated a voluminous literature (i.e. Bevan 1991, Buck 2003, Davis et al. 2000, France et al. 1992, Miller 1996, Nobes 1999, 2000, Powell 2004, Ruffell et al. 2009), well summarised by Conyers (2006) and Ruffell and McKinley (2005). The appeal of using geophysical methods for this purpose is that they are non-invasive, culturally appropriate, survey large areas relatively rapidly and can provide information about depth, orientation and other burial characteristics. Unfortunately there is no 'bone detecting instrument' (Powell 2004) as skeletal material does not, in most field situations, provide a detectable geophysical response. Geophysical techniques instead rely on locating the stratigraphic disturbance caused by the grave shaft (including the disruption of bedding, conflation of different soil layers and changes in the porosity leading to variations in water or air content), the interment vessel or the presence of metallic graves accoutrements. More intact cadavers may present additional targets relating to the presence of chest cavity voids, the contrast of the fluid rich cadaver compared to the surrounding soil or local alteration to the physio-chemical conditions from escaping fluids during decay (Bevan 1991; Davenport et al. 1990; Koppenjan et al. 2003). Unfortunately the nature of the geophysical response from any of these features is not unique and so mapping the spatial distribution of the anomalies and understanding the context of the possible burial within the broader site is essential to their successful location regardless of technique. Obviously the nature of the study area is also important and geophysics may be inappropriate for many sites, such as where the subsurface is extensively disturbed.

All of these difficulties mean that geophysics has often been used inappropriately and on occasion been derided for 'missing' burials on archaeological sites. This criticism is somewhat justified in that, regardless of the specific geophysical technique or survey methodology, these methods should not be considered a definitive means of locating graves under all circumstances and instead should form part of a suite of methods including historical research and direct investigation. However, even if these methods do not definitively locate all graves, they play a useful broader role in guiding direct investigations by allowing the extrapolation of excavation results across a site, defining the subsurface geology/geomorphology and delineating the extent of a site and any disturbance (Bladon et al. 2011).

Types of unmarked graves and investigations

Unmarked graves can have a wide range of orientations, depths, anatomical positions and degrees of decomposition depending on the burial tradition, interment circumstances, location and age. Prior knowledge of these characteristics at a particular site is extremely useful for geophysical survey design, as it will facilitate informed decision making about data density and orientation. Importantly, it is advantageous for survey lines to cross graves perpendicular to their long axis to ensure the maximum number of opportunities to image each burial.

Christian burials are usually contained within a burial vessel (often wooden) and are buried at a regular depth and orientated east-west. Multiple burials may exist in the same grave shaft, often with significant time gaps between each interment. A plethora of alternative burial configurations exist within other cultural and religious traditions and they often change over time (Pearson 1999:6). For example, Middle Palaeolithic graves are usually sufficient devoid of regular interment patterns or grave goods that the ability of Neanderthals to intentionally bury their dead has been significantly contested (ie. Gargett 1989, 1999) although new evidence for this behavior continues to emerge (Rendu et al. 2014). In contrast, the Neolithic has a plethora of different burial practices with collective burials and mortuary structures being relatively common (Fowler 2011). Roman graves have a wide variety of possible configurations including an unlined graves, tile lined graves, stone lined graves and many others (Cooke 1998: 212-221).

More elaborate burials such as crypts are usually larger, constructed of less ephemeral materials and are often designed to facilitate access for future interments. Clandestine graves have a random orientation, usually a restricted depth and rarely feature a coffin. Limited grave accoutrements such as belt buckles or clothing may be present and the body may be articulated or dismembered.

Cremated individuals may be buried in vessels or scattered. The direct detection of the burial vessel containing cremated remains is possible however it is unlikely to be distinguishable from other buried material culture unless it is contained within a very specific context (i.e. a cemetery). The fire used for the cremation may be identified geophysically (see below and Moffat et al. 2010 for further discussion) however there must exist suitable criteria for identifying the fire as being related to a mortuary event.

Equally pertinent for effective geophysical survey design is a clear understanding of the impetus for locating the unmarked graves. This issue, discussed at length in Moffat et al. (forthcoming), critically affects the ability of geophysical methods to contribute meaningfully to a particular project. The key question is whether a survey seeks to locate graves or find areas without graves; with the first application being far more demanding. Commonly, investigations for cultural heritage management purposes are focused on locating areas without burials within

a site or establishing if a site may contain burials rather than definitively locating each burial individually. Geophysics is most often employed in this type of investigation when there is a strong possibility that burials are known to exist on site, such as historic cemeteries. In this situation it is likely that a large number of possible burials will be located and few (if any) will be directly investigated. In this case the most appropriate approach to data interpretation from a risk management perspective is to consider any appropriate sized anomaly as a potential grave. Often areas identified in this way are excluded from future invasive earthworks on the site, which prevents the disturbance of graves but almost always, due to the nature of the technique, this exclusion will include areas which do not contain graves.

Definitive location of each individual grave, such as in a forensic investigation, requires a more intensive and demanding survey methodology. Invariably these investigations will require extensive direct investigation to validate the results and will benefit substantially from an iterative approach where the results of each direct investigation lead to reinterpretation of the geophysical response. While the need to validate many anomalies may appear to negate the utility of geophysics the benefit of being able to exclude large portions of the site is significant as this is very time consuming, expensive and destructive to accomplish with other techniques.

Methodological approaches

A variety of geophysical techniques, positioning methods and site recording techniques are available to detect unmarked graves. Ground Penetrating Radar (GPR) is the most widely applied technique whilst resistivity, electromagnetic induction, magnetometry and gravity are useful in specific situations. Positioning can be provided by measuring tapes and a variety of more sophisticated surveying equipment while site recording can be done using field notes, surveying equipment, photography and photogrammetry mounted on a variety of platforms.

Ground penetrating radar

Ground Penetrating Radar, summarised in respect to archaeology by Conyers (2012, 2013), works by transmitting radar energy into the ground which reflects off subsurface discontinuities in dielectric permittivity. By measuring the time taken for this energy to return to the instrument a consideration of the depth of imaged features is possible and the measurements can be combined to present the data in one, two or three dimensions. GPR surveys are most often conducted as a series of parallel transects along which the GPR antenna is dragged or pushed. These parallel data sets can be combined to create plan view maps of amplitude at a variety of depths, often referred to as slices (Goodman et al. 1995). More recently true 3D data acquisition systems utilising multiple transmitter and receivers have become available allowing much smaller interline spacing (Hunter 2012). GPR is the most commonly applied method for locating unmarked graves due to its ability to rapidly cover large areas of high density data and because, when a shielded antenna is used, it is not significantly affected by surface metal.

GPR is most likely to detect graves based on the variations in soil stratigraphy caused by grave digging (Schultz & Martin, 2011). As summarised by Damiata et al. (2013: 269) the grave shaft may be detectable based on differences in moisture content, homogeneity, compaction, structure or velocity between the disturbed and undisturbed sediment (shown in Fig. 1a). Most commonly, the most obvious sign of disturbance is the absence of the natural horizontal anisotropy characteristics of undisturbed soil (Jenny 1994, Joffe 1936). These features are most often visible in GPR data as disturbance to the A horizon. Care must be taken when interpreting these features to not falsely include anomalies created by decoupling the GPR antenna from the ground surface due to rugged topography. This can be avoided through making comprehensive field notes and by plotting the disturbance features in plan view to observe their geographic extent. Similarly, it is important to be aware of the potential impact of post-interment disturbance from animal, plant or human intrusion, especially to the stratigraphy surrounding the grave, which can make the distinction of the shaft difficult (e.g. Moffat et al. 2010).

The direct detection of graves based on hyperbola signals (high frequency reflections in a characteristic parabolic shape) is a suitable approach where there is a high contrast in dielectric properties between the burial and the sounding material such as an intact (particularly metal) coffin (Owsley and Compton 1997), metallic grave goods (Novo et al. 2010) and the presence of a vault or (very occasionally) from the skeletal material itself (Damiata et al. 2013 Pringle, et al., 2012, Schultz, et al., 2006, Schultz, 2008). The void inside a coffin can also be detected with GPR (Bevan 1991:1311; Doolittle and Bellantoni 2010:943), however untreated wooden coffins often decompose and collapse within a decade. The accurate interpretation of burials with GPR under field conditions requires dense line spacing ($\leq 0.5\text{m}$) and high quality positioning information. This degree of spatial integrity is essential so that stratigraphic breaks can be correlated accurately between multiple lines and mapped in plan view over the site (shown in Fig. 2a). This allows the geometry and extent of the soil feature to be determined allowing differentiation between graves and other soil disturbances. On sites with extensive soil disturbance (shown in Fig. 2b) it may be impossible to interpret the position of individual graves and therefore more appropriate to map larger areas as possibly containing burials.

Figure 1a: GPR data from a confidential location in South Australia.

Figure 1b: The stratigraphic break from recent burials is highlighted on the GPR section in green on the left and the location of these interpreted graves is shown in the photograph of the survey area highlighted in white.

Figure 2. a (left) and b (right): Interpretation of GPR Data from the Innamincka (left) and Lake Condah (right) cemeteries. In the Innamincka data set it is easy to define discrete area with paired stratigraphic breaks that can be confidently considered graves. In the Lake Condah data set there are large areas of the site's subsurface which are stratigraphically disturbed by tree roots in this heavily forested area, necessitating the identification of larger areas. Data collected with a Mala X3M GPR with a 500 Mhz (Innamincka) and 250 Mhz (Lake Condah) antenna.

The approach of interpreting features, particularly when focusing on stratigraphic breaks, from two dimensional profiles is much more robust than exclusively using slice mapping graves in plan view with pseudo 3D data (Goodman et al. 1995) despite the success of this approach in some surveys (i.e. Dionne et al. 2010 Schultz and Martin 2011). Slice mapping is a more suitable approach for defining features with high dielectric contrast, such as crypts (Panisova et al. 2013), intact coffins or clusters of metal features associated with a grave.

Processing of GPR data is designed to accentuate features of interest and counteract the very rapid scatter of signal (and corresponding decrease in signal to noise ratio) with distance from the antenna. The specific processing steps are site specific however a common first pass approach is to apply a dewow, bandpass filter, background remove, running average and energy decay filter. Migration may be useful to remove the common hyperbolic distortion of subsurface reflection along the acquisition path, particularly to facilitate the imaging of stratigraphic disturbance or prior to interpolation into 3D. Migration may be inappropriate for surveys aimed at locating metallic features as it will make these features less visible.

Resistivity

Resistivity, summarized for archaeological applications by Schmidt (2013), measures the resistance of earth materials to passage of electrical current. These values are measured in one, two or three dimensions by electrodes that are directly connected to the ground, usually by metal stakes. A variety of arrays are used to measure the resistivity values which affect the nature of the response. Subsurface resistivity values are strongly influenced by the inherent properties of the earth materials, their porosity, degree of water saturation and groundwater chemistry (Schmidt 2013:123-127).

Resistivity imaging in a variety of configurations has been applied to the location of burials, including in plan view with a fixed electrode interval (Pringle et al. 2012: 1473-1474), along a profile (Powell 2004) and in 3D configuration (Matias et al. 2006). The most common target for locating graves with resistivity is soil disturbance in the grave shaft which may manifest as a relative resistivity high or low (Fig. 3) compared to the surrounding soil. The relative resistivity of the anomaly compared to background will likely vary over time based on the fluid saturation of the soil pore space, which is controlled by environmental conditions. Containment of the cadaver appears to have a significant effect on resistivity values during the decay stages with an unwrapped pig cadaver appearing as a diffuse conductive anomaly whilst a wrapped pig cadaver in the same location appears as a small resistivity feature (Pringle et al. 2012: 1477). A coffin may also act as a locus for clay deposition, leading to a conductive anomaly (Powell 2004: 92). Resistivity can be used to investigate larger burial structures, without necessarily prospecting for individual burials (Papadopoulos et al. 2009, 2010, Tsourlos et al. 2014).

Electrode spacing in resistivity directly impacts the resolution and depth of investigation, with most investigations for burials requiring a maximum electrode spacing of 0.5m. A key challenge for resistivity, which has recently been somewhat ameliorated by multi-channel instruments, is that measurement is much slower than for comparable techniques such as GPR due to the need to couple the electrodes directly to the ground. This can mean that the definition of the shape and size of an anomaly can be neglected, which significantly compromises robust data interpretation. In contrast, an advantage of the use of electrodes is that the discontinuous ground coupling means that resistivity can more easily survey through crowded cemeteries where fences and grave markers may obstruct GPR investigations.

Figure 3: Inverted Resistivity Image from the Meadows' Wesleyan Cemetery, South Australia. The unmarked burials have lower resistivity values than the surrounding soils and appear in blue. Data collected using a ZZ Resistivity FlashRES-64 with a 0.75m electrode spacing.

Magnetometry

Magnetometry, summarized for archaeological applications by Aspinall et al. (2011), measures local variations in the earth's magnetic field caused by the presence of iron. The most direct application of magnetometry in the detection of graves is to locate iron associated with a burial such as grave markers, belt buckles or coffin parts (Stanger and Roe 2007). Another robust method is to detect the presence of magnetic enhancement formed in the soil surrounding the graves by burning associated with burial practices (shown in Fig. 4a) (Wallis et al. 2008, Moffat et al. 2010). There is also evidence to suggest that the fluid emitted from decaying burials increases the iron in the surrounding soil (thus increasing the magnetic intensity contrast) which may cause magnetic anomalies (Juerges et al. 2010). Similarly the presence of organic material and nutrients may facilitate magnetic enhancement through microbial colonization (Linford 2004).

Magnetometers may include single sensor, gradiometer or multi-sensor configurations with the gradiometer or multigradiometer configurations most suitable for archaeological applications. An advantage of magnetometry is that it is not significantly affected by soil disturbance and so is useful where GPR is unlikely to be appropriate (Moffat et al. 2010). A key methodological challenge in applying magnetometer to the detection of unmarked graves is recognizing that a magnetic anomaly is spatially related to a burial and not related to the abundant metal often found on the surface of cemeteries.

Electromagnetic induction

Electromagnetic induction, summarized for archaeological applications by Witten (2006), works by inducing a series of related electrical currents and magnetic fields in the subsurface between a transmitter and receiver coils. The magnitude and timing of the response allow the approximation of the apparent conductivity and magnetic susceptibility. Depth of investigation is controlled by instrument frequency or coil spacing. Electromagnetic induction has been widely applied to archaeological research (see Bigman 2012: 32 for a summary), but has only been used for the detection of unmarked graves on relatively few occasions.

Electromagnetic induction can detect graves by measuring the differences in conductivity or magnetic susceptibility (Dalan et al. 2010) in the soil caused by disturbance to the stratigraphy, by detecting metallic features in the subsurface relating to the burial such as belt buckles and coffin attachments and by locating burning signatures related to the burial activity (shown in

Fig. 4b) (Moffat et al. 2008). The soil disturbance shown by the change in the conductivity may represent mixing of topsoil with subsoil, differences in compaction or the presence of air cavities (Bevan 1991). This disturbance may appear as either resistive (Bigman 2014) or conductive (Bigman 2012, Nobes 2000) compared to surrounding soil and depending on environmental conditions, particularly soil moisture. Downhole and laboratory magnetic susceptibility methods have proved effective at locating graves (Dalan et al. 2010) however the slow and invasive nature of the coring precludes this method for most surveys.

As with all geophysical methods used for the detection of unmarked graves high resolution survey is essential to ensure the detection and resolution of targets. A maximum of 0.5m line and station spacing is necessary to ensure that all features will be located. Shorter coil spacing or higher frequencies are most appropriate for the detection of graves due to the shallow depth of the targets. As discussed in the magnetometry section above, cemeteries are often replete with surface metal making it difficult to distinguish the subtle conductivity or magnetic responses exhibited by graves. It may be possible to overcome this by removing high amplitude anomalies from the data (i.e. Marshallsay et al. 2012) however, data quality will rarely be improved to the point of being able to locate individual burials. When faced with a site with extensive surface metal other methods which are more effectively shielded from these effects such as GPR or resistivity should be strongly considered.

Figure 4. a (left) and b (right): Magnetic Intensity in nT (left) and Magnetic Susceptibility in SI Units (right) Results over Two Holocene Burials at Hack's Point, South Australia (Moffat et al. 2010). Data collected with a Geometrics

Gravity

Gravity surveying, reviewed for archaeological applications by Eppelbaum (2011), works by measuring local variations in the acceleration of the earth's gravitational field caused by differences in the density of the subsurface. This method is not suitable for the location of conventional coffin burials or clandestine graves due to their insufficient density contrast from background but is exceptionally useful in cases where a significant subsurface void may exist such as when prospecting for crypts or rock cut tombs (Panisova et al., 2013, Sarris et al. 2007). The key methodological consideration for microgravity investigations is the availability of high quality elevation and positioning data to facilitate a terrain (Fournier et al. 2004) and, in specific cases, an accurate model for building correction (Panisova et al. 2012).

Survey positioning and site recording

High quality survey positioning is essential to the successful location of unmarked burials with geophysical methods. The application is particularly demanding in this respect because of the subtle nature of the geophysical response of these targets, their small size and the need to validate them on multiple lines to effectively locate them. As well as positioning the data accurately, it is essential to locate site features that may hinder the effective interpretation of the geophysical data, such as evidence of soil disturbance, tree roots or surface metal. The most effective survey methodology is to use a combination of real time kinematic GPS and/or robotic total station for positioning the geophysical data in combination with very high resolution aerial photography from a kite or unmanned aerial vehicle to record the site. The choice between real time kinematic GPS and robotic total station will often be made by equipment availability however the degree of tree cover on the site should more correctly suggest what method is more appropriate. Very high resolution aerial photography, particularly when the photos are merged into a composite image and a Digital Elevation Model (DEM) using photogrammetry software such as Photoscan (discussed in detail in this volume by Cantoro), diminishes the burden of recording all of the surface features on the site by facilitating their mapping (see Fig. 5b). It is possible to undertake survey for unmarked graves over small areas without elaborate survey positioning (see Fig. 5a) however it relies on excellent site recording (site photos, plans and notes) and the application of the highest degree of care in starting and finishing lines correctly on the baseline so as to facilitate mapping anomalies between adjacent lines.

Data display and interpretation

In every geophysical survey for unmarked graves it is necessary to interpret and display the data in a way that is useful to the non-specialist user. Most organizations seeking these surveys have little experience in geophysics and so it is incumbent on the geophysicist to provide results which are unambiguous and easy to understand. Most often this will be a map of graves, preferably with some quantification of certainty. It is usually inappropriate to provide raw or

processed geophysical data as a survey product, except for archival purposes or to facilitate later re-interpretation by a qualified specialist. In the interpretation of any geophysical data set there will be varying degrees of uncertainty concerning each anomaly (discussed in detail by Hargrave 2006) and it is important to be able to capture this in the resulting data products. This is particularly important in cultural heritage management investigations when consumers of the geophysical data must weigh the risk of disturbing unmarked burials against the cost (both financial and emotional) of direct investigation or abandoning the site entirely.

Figure 5. a (left) and b (right): High quality survey positioning and site recording: Using survey tapes to conduct a 0.25 m station and line spaced geophysical where DPGS was ineffective due to a ring of tall trees surrounding the site (left) and high resolution site recording and photogrammetry using a pole mounted camera (right).

Despite these issues, the development of a methodology for quantifying uncertainty in the investigations of unmarked graves has been unfortunately largely ignored. A possible approach is to classify the nature of the anomalies and their relationship to each other loosely based on the conventions developed by the petroleum industry which reports reserves as ‘proved’, ‘probable’ and ‘possible’ (90%, 50% and 10% certainty of commercial extraction respectively) based on explicit diagnostic criteria (Society of Petroleum Engineers 2001). One example of such a classification scheme for GPR data for the detection of unmarked graves is a scale ranging from two adjacent stratigraphic breaks with a hyperbola between them (‘most likely’), two adjacent stratigraphic breaks without a hyperbola between them, a single stratigraphic break and a single hyperbola (‘least likely’). The flaw in this scheme is that it focuses undue consideration on the accurate interpretation of the results from an individual line and doesn’t consider the spatial relationships of the anomalies. An alternative approach is to combine considerations of the spatial distribution and nature of the anomalies. An example is described in Moffat et al. (forthcoming) in which probable anomalies are classified as ‘probable’ graves where a stratigraphic disturbance is observed on at least 4 adjacent survey lines (with a 0.5m line spacing) which has an overall size and shape consistent with an adult burial. ‘Possible’ graves are identified by 3 or more stratigraphic breaks on adjacent survey lines which have an

orientation, shape or size considered that differs from an adult burials. ‘Unlikely’ anomalies share the properties of ‘possible’ anomalies but are located in areas of the site that are outside of the area identified as a cemetery in historic records. Such an approach can be further strengthened through the use of multiple geophysical methods which all of their results merged to create a composite anomaly map (i.e. Nobes 1999).

A best practice methodology for finding graves with geophysics

Best practice geophysical survey for unmarked graves should utilize a rigorous and specialized methodology. This should include a detailed understanding of the impetus behind the survey to allow a suitable methodology to be developed. Prior knowledge of burial traditions is important to orientate the survey perpendicular to burial direction and to consider the likelihood of detecting unusual features such as crypts. GPR is the most effective method for locating graves in most cases but the exclusive use of slice maps should be avoided. GPR line spacing should be no greater than 0.5m and ideally 0.25m or less to ensure that all GPR should be supported by another survey method, most likely electromagnetic induction or magnetometry with a station spacing no greater than 0.5m required to effectively locate graves in the subsurface. Stratigraphic anomalies rather than the direct detection of skeletons should be the focus of the investigations, aided by the location of associated metal or burning features. Anomalies should be correlated across multiple lines and mapped in plan view to ensure they are of a size and shape appropriate to a grave. A rigorous scheme should be used to interpret the data which makes it accessible to the consumer and attempts to quantify uncertainty. High quality site survey positioning is essential and should be supported by intensive site recording.

Acknowledgments

My research on the location of unmarked grave with geophysical techniques has been facilitated by the generous access to a range of sensitive locations by many communities and organizations including the Ngarrindjeri, Yandruwandha/Yawarrawarrka, Albany Heritage Reference Group Aboriginal Corporation, Woolgar Valley Aboriginal Corporation, Gunditj Mirring Traditional Owners Aboriginal Corporation, Charters Towers Lions Club, City of Norwood, Payneham and St Peters and Meadows 150 Committee. This research has been facilitated by in-kind support from ZZ Resistivity Imaging, Position Partners and Ecophyte Technologies, financial support from the Sir Mark Mitchell Research Foundation and Flinders University Faculty Research Grant Scheme and through commercial contracts. Thank you also to my many collaborators on projects aimed at locating unmarked graves who have greatly influenced my thinking about this topic including, in particular Alice Beale, Paul Bladon, Nigel Chang, Larry Conyers, Julia Garnaut, Alice Gorman, Louise Holt, Brad Keene, Rob Koch, Janelle Kuter, Jon Marshallsay, Philip Mill, Mary-Jean Sutton, Chet Walker and Lynley Wallis. Julia Garnaut kindly edited this manuscript, greatly improving its clarity. Lastly, thank you to the students (particularly from my ‘Introductory Archaeological Geophysics’ topic) and other volunteers who have done most of the hard work in the field!

References

Aspinall, A., Gaffney, C. and Schmidt, A., 2011, *Magnetometry for Archaeologists*, Lanham, AltaMira.

Bevan, B.W. 1991. The search for graves. *Geophysics* 56: 1310-1319.

Bigman, D.P. 2012. The Use of Electromagnetic Induction in Locating Graves and Mapping Cemeteries: an Example from Native North America. *Archaeological Prospection* 19: 31-39.

Bigman, D.P. 2014. Mapping social relationships: geophysical survey of a nineteenth-century American slave cemetery. *Archaeological and Anthropological Sciences* 6: 17-30.

Bladon, P., I. Moffat, D. Guilfoyle, A. Beale and J. Milani 2011 Mapping anthropogenic fill with GPR for unmarked grave detection: a case study from a possible location of Mokare's grave, Albany, Western Australia. *Exploration Geophysics* 42:249-257.

Buck, S.C. 2003. Searching for graves using geophysical technology: Field tests with ground penetrating radar, magnetometry, and electrical resistivity. *Journal of Forensic Sciences* 48: 5-11.

Cooke, N. 1998. The definition and interpretation of Late Roman burial rites in the Western Europe, Unpublished PhD Thesis, Institute of Archaeology, University College London,

Conyers, L.B. 2006. Ground-penetrating radar techniques to discover and map historic graves. *Historical Archaeology* 40: 64-73.

Conyers, L.B. 2012. *Interpreting Ground-penetrating Radar for Archaeology*. Walnut Creek: Left Coast Press.

Conyers, L.B. 2013. *Ground-penetrating Radar for Archaeology*. Lanham: AltaMira.

Dalan, R.A., De Vore, S.L. and Clay, R.B. 2010. Geophysical identification of unmarked historic graves. *Geoarchaeology-an International Journal* 25: 572-601.

Damiata, B.N., J.M. Steinberg, D.J. Bolender and G. Zoëga 2013 Imaging skeletal remains with groundpenetrating radar: comparative results over two graves from Viking Age and Medieval churchyards on the Stóra-Seyla farm, northern Iceland. *Journal of Archaeological Science* 40:268-278.

Davis, J.L., Heginbottom, J.A., Annan, A.P., Daniels, R.S., Berdal, B.P., Bergan, T., Duncan, K.E., Lewin, P.K., Oxford, J.S., Roberts, N., Skehel, J.J. and Smith, C.R. (2000) Ground penetrating radar surveys to locate 1918 Spanish flu victims in permafrost. *Journal of Forensic Sciences* 45: 68-76.

Eppelbaum, L.V. 2011 Review of Environmental and Geological Microgravity Applications and Feasibility of Its Employment at Archaeological Sites in Israel. *International Journal of Geophysics* Article ID 927080.

Fournier, N., H. Rymer, G. Williams-Jones and J. Brenes 2004 High-resolution gravity survey: Investigation of subsurface structures at Poás volcano, Costa Rica. *Geophysical Research Letters* 31(15):L15602.

Fowler, C. 2010. Pattern and diversity in the Early Neolithic mortuary practices of Britain and Ireland: contextualising the treatment of the dead. *Documenta Praehistorica XXXVII*: 1-22.

France, D.L., Griffin, T.J., Swanburg, J.G., Lindemann, J.W., Davenport, G.C., Trammell, V., Armbrust, C.T., Kondratieff, B., Nelson, A., Castellano, K. and Hopkins, D. 1992. A multidisciplinary approach to the detection of clandestine graves. *Journal of Forensic Sciences* 37: 1445-1458.

Gargett, R.H. 1989. Grave Shortcomings: The Evidence for Neandertal Burial. *Current Anthropology* 30(2): 157-190.

Gargett, R.H. 1999. Middle Palaeolithic burial is not a dead issue: the view from Qafzeh, Saint-Cesaire, Kebara, Amud, and Dederiyeh. *Journal of Human Evolution* 37: 27-90.

Goodman, D., Nishimura, Y. and Rogers, J.D., 1995. GPR time slices in Archaeological Prospection, *Archaeological Prospection*, 2, 85-89.

Gowland, R. and C. Knusel (eds) 2009 *The Social Archeology of Funerary Remains. Studies in Funerary Archaeology*. Oxford: Oxbow Books.

Hunter, D. 2012 The Malå MIRA at the Wallaga Lake Aboriginal Cemetery. *ISAP News* 31:2-4.

Jenny, H. 1994. *Factors of Soil Formation: A System of Quantative Pedology*. Dover Publications, New York.

Joffe, J. 1936. *Pedology*. Rutgers University Press, New Brunswick.

Killam, E.W. 1990 *The Detection of Human Remains*. Springfield: Thomas.

Linford, N.T. 2004. Magnetic ghosts: mineral magnetic measurements on Roman and Anglo-Saxon graves. *Archaeological Prospection* 11: 167-180.

Marshall, J., I. Moffat and A. Beale 2012 Geophysical Investigations of the Tabernacle (Yilki) Cemetery, Encounter Bay, South Australia. *Journal of the Anthropological Society of South Australia* 35:91-103.

Matias, H.C., F.A.M. Santos, F.E.R. Ferreira, C. Machado and R. Luzio 2006 Detection of graves using the microresistivity method. *Annals of Geophysics* 49(6):1235- 1244.

Miller, P.S. 1996. Disturbances in the soil: Finding buried bodies and other evidence using ground penetrating radar. *Journal of Forensic Sciences* 41: 648-652.

Moffat, I., Gorman, A., Harding, T., Ross, P., Garnaut, J. and Petruzzelli, B. Forthcoming. *Non-Destructive Cultural Heritage Management of Unmarked Graves: A Case Study from Gladstone Cemetery, Queensland*.

Moffat, I., Wallis, L.A., Hounslow, M.W., Niland, K., Domett, K. and Trevorrow, G. 2010. Geophysical Prospection for Late Holocene Burials in Coastal Environments: Possibilities and Problems from a Pilot Study in South Australia. *Geoarchaeology: An International Journal* 25: 645-665.

Morrall, P. 2006 *Murder and Society*. Chichester: John Wiley & Sons.

Nobes, D.C. 1999. Geophysical surveys of burial sites: A case study of the Oaro urupa. *Geophysics* 64: 357-367.

Nobes, D.C. 2000. The search for 'Yvonne': A case example of the delineation of a grave using nearsurface geophysical methods. *Journal of Forensic Sciences* 45: 715-721.

Owsley, D. and B. Compton 1997 Preservation in late 19th century iron coffin burials. In W. Haglund and M. Sorg (eds), *Forensic taphonomy: the postmortem fate of human remains*, pp.511-526. Boca Raton: CRC Press.

Panisova, J., M. Fraštia, T. Wunderlich, R. Pašteka and D. Kušnirák 2013 Microgravity and Ground-penetrating Radar Investigations of Subsurface Features at the St Catherine's Monastery, Slovakia. *Archaeological Prospection* 20(3):163-174.

Panisova, J., R. Pašteka, J. Papco and M. Fraštia 2012 The calculation of building corrections in microgravity surveys using close range photogrammetry. *Near Surface Geophysics* 10(5):391-399.

Papadopoulos, N.G., M.-J. Yi, J.-H. Kim, G.N. Tsokas, P. Tsourlos and A. Sarris 2009 Tumuli exploration using surface 3D Electrical Resistivity Tomography. *ArchéoSciences* suppl. 33:129-132.

Papadopoulos, N.G., M.J. Yi, J.H. Kim, P. Tsourlos and G.N. Tsokas 2010 Geophysical investigation of tumuli by means of surface 3D Electrical Resistivity Tomography. *Journal of applied Geophysics* 70(3):192- 205.

Pearson, M.P. 1999 *The Archaeology of Death and Burial*. College Station: Texas A&M University Press.

Pettitt, P.B. 2010 *The Palaeolithic Origins of Human Burial*. London: Routledge.

Powell, K. 2004. Detecting buried human remains using near-surface geophysical instruments. *Exploration Geophysics* 35: 88-92.

Pringle, J.K., Jervis, J.R., Hansen, J.D., Jones, G.M., Cassidy, N.J. and Cassella, J.P. 2012. Geophysical Monitoring of Simulated Clandestine Graves Using Electrical and Ground-Penetrating Radar Methods: 0-3 Years After Burial. *Journal of Forensic Sciences* 57: 1467-1486.

Rendu, W., Beauval, C., Crevecoeur, I., Bayle, P., Balzeau, A., Bismuth, T., Bourguignon, L., Delfour, G., Faivre, J.-P., Lacrampe-Cuyaubère, F., Tavormina, C., Todisco, D., Turq A. and Maureille B. 2014. Evidence supporting an intentional Neandertal burial at La Chapelle-aux-Saints. *Proceedings of the National Academy of Sciences* 111(1): 81-86.

Ruffell, A., McCabe, A., Donnelly, C. and Sloan, B. 2009. Location and Assessment of an Historic (150-160 Years Old) Mass Grave Using Geographic and Ground Penetrating Radar Investigation, NW Ireland. *Journal of Forensic Sciences* 54: 382-394.

Ruffell, A. and McKinley, J. 2005. Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations. *Earth-Science Reviews* 69: 235-247.

Rynearson, T. 1994 Psychotherapy of Bereavement After Homicide. *Journal of Psychotherapy Practice and Research* 3(4).

Sarris, A., R.K. Dunn, J.L. Rife, N. Papadopoulos, E. Kokkinou and C. Mundigler 2007 Geological and geophysical investigations in the Roman cemetery at Kenchreai (Korinthia), Greece. *Archaeological Prospection* 14(1):1-23.

Schmidt, A. 2013. *Earth Resistance for Archaeologists*. Lanham: AltaMira.

Society of Petroleum Engineers. 2001 *Guidelines for the Evaluation of Petroleum Reserves and Resources*. Richardson: Society of Petroleum Engineers.

Stanger, R. and D. Roe 2007 Geophysical surveys at the West End Cemetery, Townsville: an application of three techniques. *Australian Archaeology* (65):44-50.

Tarlow, S. and S. L.N. (eds) 2013 *The Oxford Handbook of the Archaeology of Death and Burial*. Oxford Handbooks in Archaeology. Oxford: Oxford University Press.

Tsourlos, P., N. Papadopoulos, M.J. Yi, J.H. Kim and G.

Tsokas 2014 Comparison of measuring strategies for the 3-D electrical resistivity imaging of tumuli. *Journal of applied Geophysics* 101:77-85.

Wallis, L.A., Moffat, I., Trevorrow, G. and Massey, T. 2008. Locating places for repatriated burial: a case study from Ngarrindjeri ruwe, South Australia. *Antiquity* 82: 750-760.