REVIEW OF GEOPHYSICAL APPLICATIONS

in Australian archaeology

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Abstract

Multidisciplinary approaches are now commonplace in the investigation of archaeological sites worldwide. Consequently, geophysics has become an increasingly important tool for reconstructing past landscapes and investigating research questions. However, despite their acceptance internationally, in Australia the use of geophysical techniques on archaeological sites has been underutilised. This paper examines the history of archaeological geophysics in Australia and seeks to understand, given their potential advantages, the role that factors such as costs, time, instrument availability and lack of theoretical knowledge have played in the underrepresentation of these methods in local archaeological investigations to date. With the recent introduction of short courses in archaeological geophysics to at least one Australian tertiary institution, this review is a timely overview of where this discipline has been, what it has to offer and whether there is potential for Australian archaeologists to develop the skills necessary to conduct archaeological geophysic investigations, as their international counterparts do already, in the future.

Introduction

Interdisciplinary studies are extremely useful for investigating archaeological sites, with a growing interest in broadening their usage in the understanding of landscapes (Anschuetz *et al.* 2001; Campana and Piro 2009; Ciminale *et al.* 2009; Dalan *et al.* 2003; Keay *et al.* 2009; Kvamme 2003). Geophysics, geoarchaeology, satellite remote sensing and geographic information systems (GIS) are just a few methods that can be used jointly to reconstruct archaeological landscapes, thereby enhancing our understandings of site formation processes, settlement patterns and human-environment interactions. Likewise, archaeological geophysical techniques have been applied routinely for mapping sites, but also to address more sophisticated research questions (e.g. Conyers and Leckebusch 2010; Dalan *et al.* 2003; Gaffney and Gator 2003:23; Johnson 2006). Archaeological geophysical studies have been so prolific that a specialist journal, *Archaeological Prospection*, and the International Society for Archaeological Prospection (ISAP) were established in the 1990s to provide forums in which this type of research could be presented and discussed (Apsinall *et al.* 2008). Geophysical methods have now become part of the standard archaeological science teaching regime in British and other European and North American universities. Television programs such as *Time Team* and *Time Team America* have also popularised their usage.

However, in comparison to their international adoption, in Australia the use of geophysical techniques for archaeological studies has been rare. Nevertheless, there is a growing local interest in these methods, driven by factors including their non-destructive nature and their capacity to rapidly assess subsurface archaeological remains, which afford potential benefits in the cultural heritage management arena, as well as their ability to provide information not easily available via other means (e.g. Gibbs and Gojak 2009; Hall and Yelf 1993; Moffat *et al.* 2008, 2010; Ranson and Egloff 1988; Stanger and Roe 2007; Wallis *et al.* 2008). The rarity of geophysics to date may be due to perceived high costs of specialised staff and equipment, the availability (or lack thereof) and suitability of instrumentation and/or skilled operators, and the subtle nature of targets in subsurface Indigenous sites, compounded by the lack of training and support available in university departments (Moffat *et al.* 2008; Powell 2004). This paper examines the history of archaeological geophysics in Australia and seeks to understand why, given their potential advantages, these methods have been so underrepresented in Australian archaeological investigations particularly as they were first introduced here in the 1970s.

Geophysics and Landscape Archaeology

As geophysics are so widely used for investigating 'landscapes', it is appropriate first to examine what is meant by this term. While there is no single definition for landscape, its meaning has both objective and subjective implications. Those who see landscapes more objectively may relate to a definition provided by Roberts (1987:77), whereby landscapes are 'the physical framework within which human societies exist'. Others have defined landscapes as 'a mode of human communication, a medium within which social values are actively debated and symbolically realised' (Wagner 1972:43-61). Stilgoe's (1982:3) definition, that landscapes are 'land shaped by humans, land modified for permanent human occupation such as a dwelling, agriculture, manufacturing, government, worship and pleasure', implies that humans are the creators of landscapes through design processes. Amongst the multiple definitions for landscapes, all include one central theme: humans. Landscapes are constructions and compositions of the world as made and viewed by humans (Cosgrove 1984; Jackson 1995); a term more frequently used as humans become more conscious of, and concerned with, their visible surroundings.

Perceiving landscapes as a central concept in archaeological research is a relatively recent development (Dalan *et al.* 2003:20). Archaeologists studying landscapes have attempted to understand sites in terms of changing time, environments and space, in the context of other factors including social and political organisation. The first landscape approach in archaeology, which came to be known as cultural ecology, was by the geographer Karl W. Butzer (1978). Butzer applied a

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systems approach to analyse the dynamic interactions between societies and their environments (the latter divided into phenomena such as flora, fauna, geomorphology, climatology etc), emphasising settlement and subsistence. These concepts were subsequently applied by others, including Binford (1987), Meggers (1979), and Rossignol and Wandsnider (1992), who maintained the ideas of geology and ecology in spatial human land-use interpretations. Rossignol (1992:4) defined a landscape approach as the archaeological investigation of past land-use by means of a landscape perspective, combined with the conscious incorporation of regional geomorphology and actualistic studies (e.g. taphonomy, formation processes, ethnoarchaeology), and marked by ongoing re-evaluation and innovation of concepts, methods and theory. The polarisation in archaeology between concepts of landscape that emphasise settlement and subsistence questions, versus those that focus on social and symbolic aspects leads to two different approaches (Dalan *et al.* 2003:21). The first involves landscape as a system (regional), and refers to the need to place sites within an overall pattern of on- and off-site activities (Foley 1981). This sees an integration of sites within settlement and subsistence systems that are suited to various economic, political and social structures (Preucel and Hodder 1996:32). The latter involves the understanding of landscape through individual experience and attempts to investigate how landscapes are perceived to be meaningful by humans, an area otherwise known as 'phenomenology' (Tilley 1994; Wilkinson and Stevens 2003).

In either case, archaeological landscape approaches encompass a broad spectrum of understanding of both cultural and natural environments (Anschuetz *et al.* 2001:157-158) and, in the broadest sense, involve studying the physical alteration of the latter (Lawrence and Low 1990:454) – it is these physical alterations of the natural environment that can be studied through archaeological geophysics. Geophysical techniques are well-suited for detecting features such as buried architecture, dwellings, roads, middens and other constructions that give meaning to human occupations (Campana and Piro 2009; Kvamme 2003). Because archaeological prospecting should be understood as the science of exploration of the landscape for detecting human activity (Aspinall *et al.* 2008), it seems only natural that these two concepts, landscape and archaeological geophysics, be linked more closely.

Archaeological geophysics is defined as the examination of the Earth's physical properties using non-invasive ground survey techniques to reveal buried archaeological features, sites and landscapes (Gaffney and Gator 2003:12). The general premise behind these methods is that the physical and chemical properties associated with buried archaeological objects will be different to those of the matrix that surrounds them (Clark 1996; Gaffney and Gator 2003:25; Johnson 2006). For example, many anthropogenic behaviors lead to local alterations in the natural landscape, such as the additional compaction that would occur inside a dwelling compared to the soil immediately adjacent and outside, the construction of a baked clay oven for cooking food, the transfer of soil from one location to another as might occur during construction of a ditch, mound or earthen embankment, or the discard of refuse such as shells. These physical and chemical differences can be measured and mapped using geophysical instruments, thus leading to a better understanding of spatial relationships and depositional environments between buried features and the landscape.

Common Geophysical Techniques used in Archaeology

Geophysical applications in archaeology did not become popular until the emergence of processual archaeology, with its greater emphasis on scientific applications and rigour (Bevan and Kenyon 1975; Fischer 1980; Scollar 1971; Weymouth 1979, 1986). As a consequence of advances in instrument sensitivity, data acquisition and processing speed, computing power, and greater affordability, their usage grew steadily through the 1980s and 1990s, especially in Europe and North America (Kvamme 2001, 2003).

There are four standard geophysical methods currently used in archaeological prospection and that are discussed below: (1) electrical resistance; (2) electromagnetic conductivity; (3) magnetometry; and, (4) ground penetrating radar (GPR). Magnetic susceptibility, a less commonly used technique, is also discussed. With the exception of magnetometry all are active methods, meaning they send signals into sedimentary deposits and map the physical and chemical responses to that signal. The following section describes briefly the theoretical framework as it relates to archaeological prospection for each of the methods; detailed theoretical explanations for how each method works are available elsewhere (e.g. Reynolds 1997).

Electrical Resistance

Electrical resistance uses actively induced electrical currents to measure a material's resistance to the flow of electricity. The basis for this method is that electric currents are directed into the ground and the resistance to their flow through the soil is measured – resistance varies depending on factors including water content, porosity and chemistry (e.g. presence of salts) (Clark 1996:27; Gaffney and Gator 2003:26). Buried cultural remains, such as roads, structures, walls, pits, ditches and shell middens, often have physical and chemical properties that allow them to be imaged using this technique (Figure 1).

For archaeological purposes a typical resistance survey will use four electrodes (or 'probes') which introduce a known current into the ground, whereby two of the electrodes act as the current and the other two act as the potential. The electrodes are commonly spaced at either 0.25, 0.50 or 1.0 m apart and can be manifested in any number of arrays. The two most common arrays are: (1) Twin, where two electrodes are mobile and the other two are placed at a distance measuring at least 30 times that of the distance between the two mobile electrodes; and, (2) Wenner, where the electrodes are equally spaced and are moved together (Clark 1996:Figure 36; Gaffney and Gator 2003; Somers 2006). The recent development of a 'multiplexer' allows multiple logging modes to be utilised during resistivity surveys, resulting in more rapid data acquisition.

Another form of resistance is electrical resistivity tomography (ERT), which is most commonly used in geological and environmental investigations but in the last decade has been applied to archaeology with encouraging results (e.g. Astin *et al.* 2007; Clark 1996; Compare *et al.* 2009; Drahor *et al.* 2008; Ortega *et al.* 2010). Unlike standard resistance surveys, which

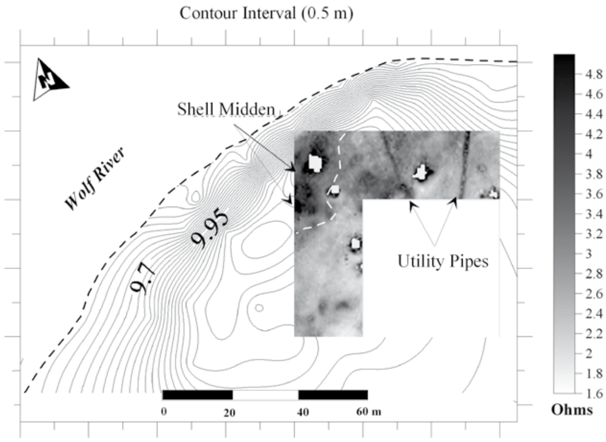

Figure 1 An example of a resistance image from the Oak Grove site (22HR502), a Middle Woodland to Late Mississippian (ca AD 400-1240) shell midden site located on a bluff overlooking the Wolf River. High resistance areas such as shell midden deposits are shown in dark grey and the dotted white line indicates the shell midden's inland extent (Lowe *et al.* 2010).

are typically used to map shallow subsurface features, ERT can measure features at depths greater than twin-probe resistance surveys and has been used on sites containing deeply buried monumental structures such as tells (e.g. Casana *et al.* 2008). It can also be used to map smaller, shallower features such as graves (Stringfield *et al.* 2008) (Figure 2). Widely-spaced electrodes allow measurements to be taken at greater depths, while narrowly-spaced electrodes offer higher resolution near the surface.

Electromagnetic Conductivity

Another active method is electromagnetic conductivity (EM). EM, or an 'induction meter', is used as a way to detect differences in the conductivity of subsurface materials by measuring the ease with which current flows through them (Bevan 1998). In contrast to resistivity, EM does not involve any direct contact with the ground. Instead, it works by inducing a primary electromagnetic field located at one end of the instrument which produces a second magnetic field that induces the flow of eddy currents into the ground and which is then received by a second coil located at the other end of the instrument (Reynolds 1997). The indirect coupling from the transmitter coil through the Earth's surface and back to the receiver coil allows electrical conductivity to be measured (Bevan 1998). Changes in the magnitude of secondary eddy current are a direct reflection of differences in the electrical conductivity of subsurface sediments (Conyers *et al.* 2008).

When using EM instruments for archaeological prospection, the operator has the option of choosing to measure the quadrature (Q) phase (i.e. conductivity) of the electromagnetic wave or the in-phase (IP) (i.e. magnetic susceptibility, which is discussed in more detail later). The quadrature is a measure of the electrical component and is expressed in millisiemens (mS), while the in-phase component is a measurement of the magnetic component of the electromagnetic wave and is expressed in parts per thousand (ppt) (West and Macnae 1991). The former is dependent on soil porosity, water content and permeability, while the latter is more sensitive to metallic objects (McNeill 1980). Fortunately, both components can be measured simultaneously, providing a quick and rapid geophysical site assessment, with each equally suitable for mapping brick and stone foundations, house structures, walls, ditches, pits, extinct river channels and mound remnants, such as ploughed mounds (Figure 3).

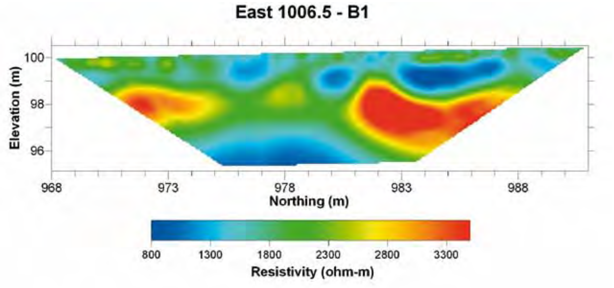

Figure 2 An example of electrical resistance tomography on the historic St Michaels Cemetery in Pensacola, Florida. Low resistivity anomalies located at ca 976.5 and 980 m north indicate unmarked graves and the long, low resistivity anomaly between 983 and 987 m north could also indicate a row of graves (Stringfield *et al.* 2008). Image courtesy of Aaron Fogel.

Ground Penetrating Radar

Ground penetrating radar (GPR), probably the most popularly recognised geophysical method, works by actively emitting radar waves into the ground. When these waves encounter materials with different physical and/or chemical properties or relative dielectric permittivity (RDP), a reflection occurs, sending part of the wave back to the surface, where it is received and recorded by the instrument. The remainder of the wave continues downward until parts of it are reflected back to the surface by deeper objects or it dissipates from being absorbed by subsurface materials. In more technical terms, GPR involves electromagnetic energy 'composed of conjoined electrical and magnetic fields' being propagated by an emitting antenna contained within the GPR unit when an oscillating current is applied (Conyers 2004:23). When a high frequency is applied a short wavelength results, providing a high resolution view of the subsurface though the wave does not transmit to a great depth (approximately 0.5-1.0 m). Inversely, when a low frequency is applied a long wavelength is created, providing less resolution but enabling much deeper transmission of the wave (up to 8-10 m). RDP is a measure of the ability of a material to hold and transmit an electromagnetic charge and is determined by the composition, moisture content, bulk density, porosity, physical structure and temperature of a material (Conyers and Goodman 1997:32; Olhoeft 1981). The time which transpires between transmission and reception is measured in nanoseconds (nS) and mathematical calculations are able to approximate the depth at which a reflection occurred. GPR studies have been conducted on a variety of site types and have been used to locate pits, ditches, house structures and walls, burials, pipes and roads (Figure 4).

Magnetometry

In contrast to the aforementioned active techniques, magnetometry is a passive method that measures the strength or alteration of the earth's magnetic field across an area (Aspinall *et al.* 2008; Bevan 1998; Clark 1996; Gaffney and Gater 2003; Kvamme 2006; Witten 2006). Localised differences in this field are defined as 'anomalies', and are generally associated with iron-rich material. Magnetometers can be used in two

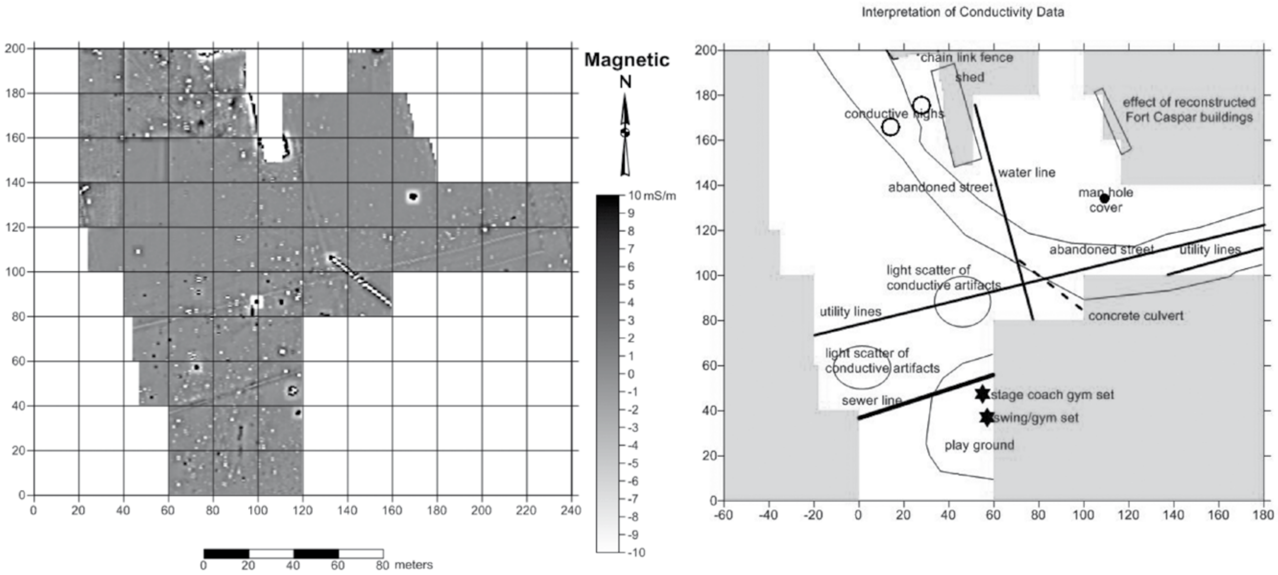

Figure 3 (Left) An example of an electromagnetic conductivity image of the Fort Caspar 1865 military post. (Right) Interpretation of the image showing modern disturbances as well as an abandoned street and two light scatters, probably metal artefacts, in the general vicinity of a demolished house and a nineteenth century fort (DeVore 1988). Images courtesy of Steve DeVore.

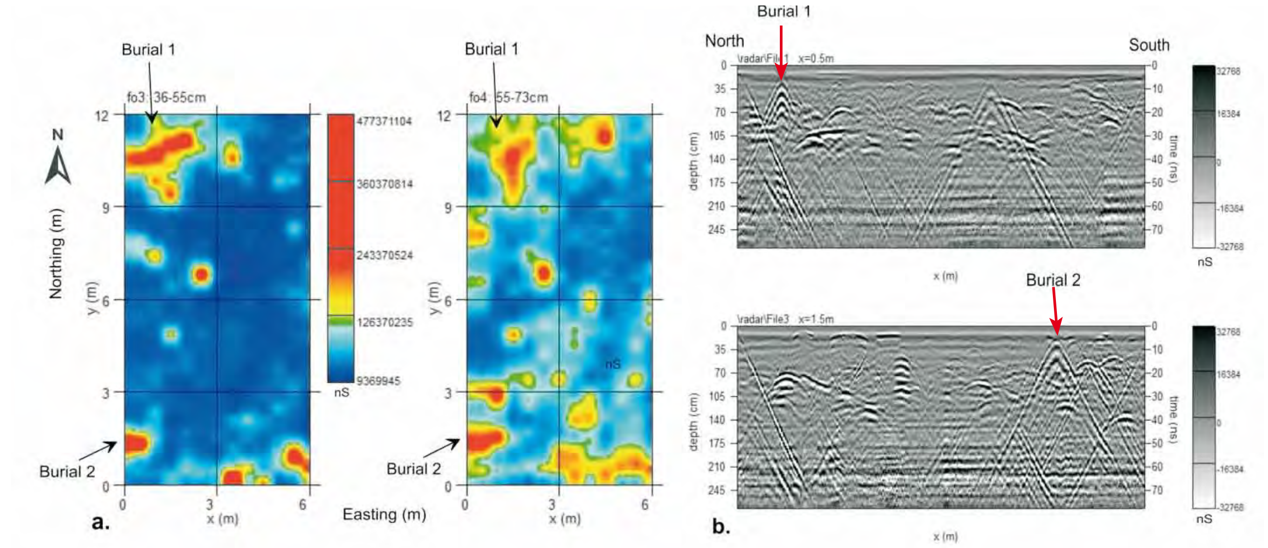

Figure 4 An example of a GPR image of the Foley Plot, located in Krebs Cemetery which is part of the historic La Pointe Krebs House, ca 1700s. GPR was used to located unmarked graves that had been disturbed (i.e. their headstones removed) by Hurricane Katrina. (a) An amplitude slice-map showing the location of two burials; (b) A GPR reflection profile showing the two burials identified in the amplitude slice map (Lowe 2011).

different modes, a single-sensor mode which measures the total magnetic field of the earth, and a two-sensor mode – known as a gradiometer – whereby two sensors measure the local magnetic field simultaneously. Unlike the single-sensor magnetometer, gradiometers do not allow for the measurement of depth: the magnetic sensors are located vertically at opposite ends of the instrument allowing measurement of the vertical gradient or change of the magnetic field between them, expressed in nanoTeslas (nT), though an approximate depth can be estimated by analysing the magnetic signal. The advantage of gradiometers is that the background signal is removed, allowing archaeological features to stand out more clearly.

Generally, objects with aligned magnetic minerals will produce higher readings than those without such alignment. Archaeologically, magnetometry is capable of mapping features with remnant magnetisation, such as hearths, ditches, graves associated with metal (e.g. caskets, headstones or funerary objects), areas of mounded topsoil and pits with enhanced magnetic susceptibility (Aspinall *et al.* 2008; Gaffney and Gator 2003; Witten 2006) (Figure 5).

Magnetic Susceptibility

Magnetic susceptibility (MS) can potentially be considered a fifth geophysical technique, since it uses induced magnetisation, though it is generally discussed under electromagnetic conductivity or magnetometry in respect to archaeological prospection. MS is a measure of the ease with which a material can be magnetised and is defined as the ratio of the induced magnetisation to the inducing field, i.e. it quantifies the response of a material to an external (weak) magnetic field (Dalan and

Banerjee 1998:6; Thompson and Oldfield 1986:25). Unlike magnetometry, which records spatial variations in the earth's magnetic field, MS measures the permanent magnetisation of that field after it has been magnetised. Interestingly, using the IP component of EM instruments (as previously discussed), MS can be investigated over large areas, and MS instruments can measure finer increments in both down-hole and lab-based applications (Figure 6). Archaeologically, MS has been used to locate pit and ditch features, identify burnt objects and define buried cultural layers. It has also been used to map features vertically, to build and correlate stratigraphic sequences, and assist in understanding site formation and post-depositional processes (Dalan 2001:263). Investigations have also included its use in trenches and excavations, soil profiling and three-dimensional data cubes (Dalan 2008) (Figure 7).

The History of Archaeological Geophysics in Australia

The rarity of archaeological prospection in contemporary Australian archaeology is somewhat unexpected, as these methods were being used locally in the mid-1970s when they were also emerging in Europe and North America. The first geophysical applications in Australian archaeology were undertaken by John Stanley (1975) from the University of New England. Stanley conducted several tests to determine whether a magnetometer could identify hearths and shell middens in the landscape and could be used in burial detection (Connah *et al.* 1976; Stanley 1983; Stanley and Connah 1977; Stanley and Green 1976). This early research focused primarily on whether or not geophysical methods would be *applicable* in the Australian context, because here most archaeological sites and features were not thought to be substantive enough to cause detectable physical and chemical differences to the landscape (Tite 1972:43). Stanley's research disproved this belief by convincingly demonstrating that magnetometry was indeed suitable for mapping hearths, middens and burials. In addition to demonstrating the viability of geophysics in Australian archaeology, comparisons of two different magnetic instruments – the proton precession and caesium vapour magnetometer – were conducted to determine the most efficient and cost-effective instrument for field use. Stanley and colleagues demonstrated that the much cheaper (at approximately one-quarter the price) proton precession magnetometer was much slower (taking 10 measurements per minute) than the caesium vapour magnetometer (which took 3000 measurements per minute).

Yet despite this promising beginning, uptake of this new technology remained minimal, with no further terrestrial studies being published through the 1980s, though a new innovation in Australian maritime archaeology emerged. Cushnahan and Staniforth (1982:64) used a proton precession magnetometer to detect magnetic signals from vessels now buried in dune deposits. Their work demonstrated that vessels with both high and low magnetic signals could be detected using magnetometry, even in areas that contained naturally magnetic materials like sands and basalt rocks, and therefore that this technique would be suitable for detecting shipwrecks.

Geophysics did not make an appearance again until the end of the 1980s with the introduction of electrical resistance to the technologies previously piloted. Ranson and Egloff (1988) demonstrated the applicability of the Gossen Geohm 3 resistivity meter via two case studies: one locating graves in cemeteries and the other identifying features at an historic site. In the former, unmarked graves in the Wybalenna cemetery, southern Australia, were identified using non-invasive geophysical techniques which proved successful because burials contain a different soil structure to that surrounding them. In their second study, Ranson and Egloff (1988:64) used resistance to locate old paths, carriageways and gardens at Port Arthur, Tasmania, with confirmation of their findings being subsequently provided through traditional excavation. Ranson and Egloff's work also provided an example of how geophysical applications could be used to assist in site management. In their first study they were able to identify the spatial extent of a cemetery, critical information for future site protection and management strategies. In their second study they used both the geophysical and archaeological results to provide information about the site's physical layout, which assisted in the conservation, planning and restoration of the site. Their work was an excellent example of early geophysical applications in archaeology, and provided readers with a detailed explanation of the particular instrumentation and data processing methods used, and addressing issues including time, cost and survey methodology, all of which were a concern to researchers contemplating using geophysics in this early period.

Applications in historical archaeology continued in the 1990s with the work of Hall and Yelf (1993), who introduced GPR in combination with magnetometry to locate subsurface features around an historic tower mill site in southern Queensland. Like Ranson and Egloff, Hall and Yelf (1993:121) wanted to provide a non-invasive way to locate cultural remains that could assist in site redevelopment, proposing that their approach was a more cost-effective, time efficient and less destructive means to understand subsurface deposits than traditional archaeological methods (Hall and Yelf 1993:121). They identified a pit and occupational layer using GPR and discovered at least 17 magnetic anomalies. While their archaeological findings were minimal, in that no additional information on the site's settings (e.g. paths, roads or structural remains) were provided (or at least reported) in their research, they demonstrated that GPR was capable of mapping historic cultural remains in the Australian context. Although they identified 17 magnetic anomalies, they also encountered a lot of noise (i.e. interference from power-lines and iron roofs) which may have affected their results. Since no anomalies were subsequently investigated through excavation, their determination as to the origins of the magnetic anomalies (i.e. whether they were caused by modern noise or the presence of subsurface historic features) remains unknown. However, their study did show the difficulties of using magnetometry in areas containing abundant potential sources of interference (e.g. metal fences, power lines or roofs) – an important issue in geophysical prospecting that has not yet been resolved, meaning that some techniques are better than others for use in urban settings.

Australian GPR applications continued with work by Randolph *et al.* (1994), and Yelf and Burnett (1995), who both used the method for locating unmarked graves. Randolph *et al.* (1994) used GPR as a non-invasive method for locating burials in an Aboriginal prisoner cemetery located on Rottnest Island, southwest Australia. The same approach was used by Yelf and Burnett (1995) for locating two Aboriginal cemeteries

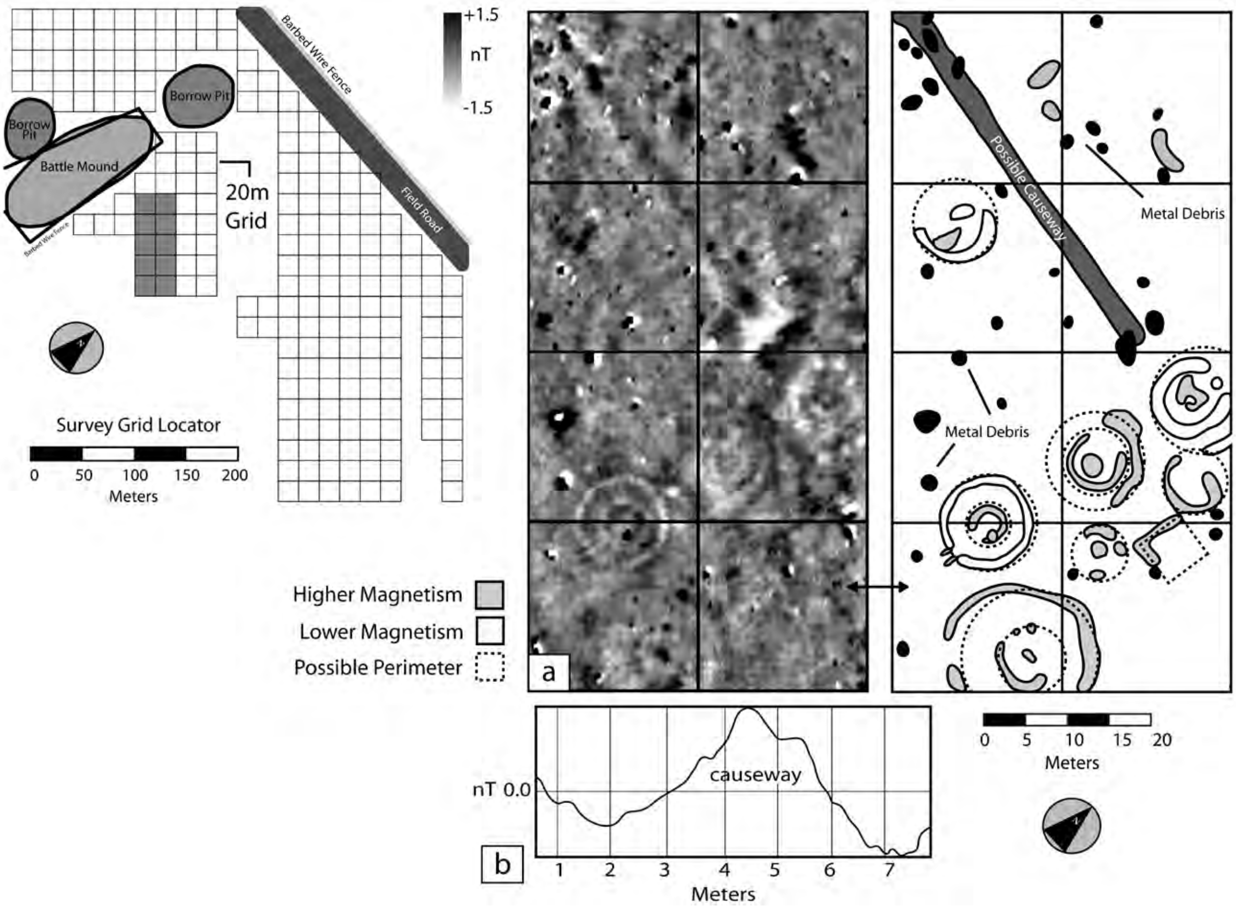

Figure 5 A comparison of circular anomalies at the Battle Mound site (3LA1), a Middle-Late (ca AD 1200-1700) Caddo mound site. (a) A magnetic gradiometry image from an area directly east of the large platform mound; (b) Graph representation of a single traverse of magnetic gradiometry data over an area 200 m east of the mound showing a causeway. Image courtesy of Duncan McKinnon.

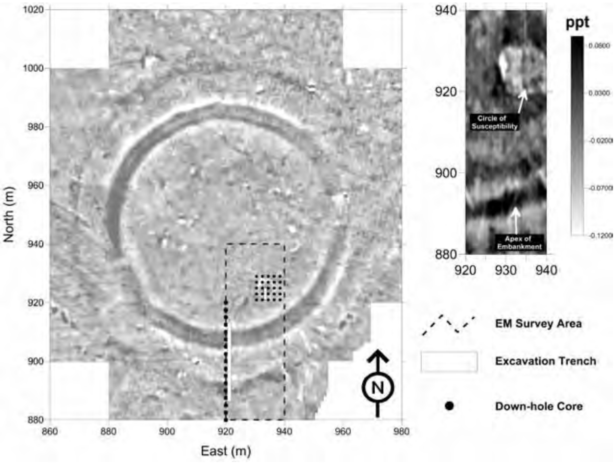

Figure 6 A multistage geophysical approach at the LeBus Circle earthwork. (Left) A gradiometer image displayed at 50% opacity showing the circular earthwork and the location of down-hole magnetic susceptibility cores as black dots. (Right) A magnetic susceptibility image showing a circular anomaly with high susceptibility within the earthwork. Image courtesy of Edward R. Henry.

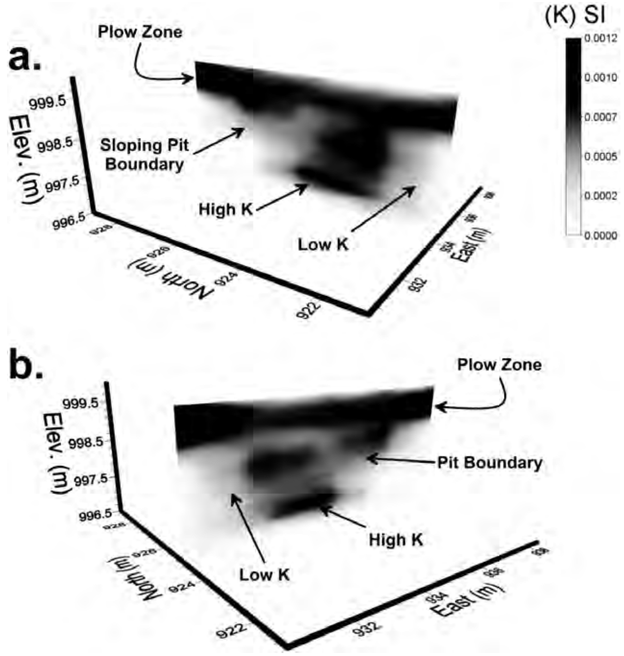

Figure 7 A north-south profile of down-hole magnetic susceptibility through the centre of the circular anomaly or area of high susceptibility within the LeBus Circle earthwork (see previous figure), also defined as a pit feature. Image courtesy of Edward R. Henry.

at Bundulla, southeast Queensland. Since applications using GPR for burial detection were rare at this time, Randolph *et al.* (1994:408) initially conducted preliminary surveys on known burials, a critical factor in subsequently allowing them to identify unmarked burials at the cemetery of interest. Yelf and Burnett (1995:20-24), with a background in exploration geophysics, relied on their theoretical knowledge of GPR data and the local geology to successfully detect burials at Bundulla.

In the first decade of the new millennium, a growing interest in archaeological prospecting in Australia has emerged, with locating buried human remains being the most common use for such techniques (e.g. Brown *et al*. 2002; Long and von Strokirch 2003; Moffat *et al.* 2010; Powell 2004, 2010; Stanger and Roe 2007; Wallis *et al.* 2008). In such research, the concern has not been to determine whether such techniques will work – because this has long been known (e.g. Bevan 1991; Davenport 2001; France *et al.* 1992; Nobes 2000) – but rather to determine which method, or combination of methods, works best in which particular environment. The most frequently used geophysical instrument documented for detecting graves in Australia has been GPR (e.g. Brown *et al*. 2002; Long and von Strokirch 2003; McDougall *et al.* 1997; Moffat *et al.* 2010; Powell 2004, 2010; Randolph *et al*. 1994; Sutton and Conyers in prep.; Wallis *et al.* 2008; Yelf and Burnett 1995), led by the purchase of this equipment by James Cook University through an initiative led by historical archaeologist Martin Gibbs, with other universities following suit. Nevertheless, studies have shown that resistance and EM may sometimes be better suited for the detection of burials, owing to the contrasts in the physical properties or soil moisture content of grave fill sediments compared with surrounding soils. Likewise, where magnetic minerals can be expected to be associated with a burial, such as a metal casket, cremation or ochre in funerary practices, magnetometry may be a better indicator of human remains than GPR. Further, the use of GPR for burial detection in certain environments, such as aeolian sand dunes, has been shown to be sometimes ineffectual (e.g. Moffat *et al*. 2010). Despite these limitations, GPR has also been used successfully for locating structural remains and human trackways (e.g. Webb 2007).

A shift towards using multiple instruments for archaeological prospection is also apparent in recent studies. Questions surrounding the nature of detected anomalies, especially complex GPR anomalies, can be addressed more successfully when integrated with multiple geophysical data sets. Brown *et al.* (2002) found that both GPR and magnetometry (von Strokirch 1999) were complementary in the detection of burials at the Ebenezer Mission cemetery, western Victoria. For Stanger and Roe (2007:49), neither GPR nor resistance methods were as successful as magnetometry at detecting burials at an historic cemetery in northern Queensland; however, after comparing the two datasets they *were* able to demonstrate that some magnetic anomalies appeared in the same location as GPR anomalies, thus suggesting a correlation.

Multiple method surveys, in which some instruments worked better than others, have also been reported by Moffat *et al.* (2008), who used both EM and magnetometry for investigating Aboriginal open sites in northwest Queensland, and Gibbs and Gojak (2009), who used a combination of GPR, resistance and magnetometry for locating historic structural remains in urban Sydney. Although Moffat *et al.* (2008:62) did not find any hearths or midden features with magnetometry, they did detect a burial with EM, and found that both techniques were suitable for mapping subsurface geology. Gibbs and Gojak (2009) found GPR to be the most satisfactory of the three methods they used, since it allowed for the targeting of anomalies more closely through the production of time-sliced, three-dimensional data showing depths. Magnetometry proved least successful in identifying historic features because of high levels of contemporary metal in the survey area overshadowing the historic data of interest (cf. Hall and Yelf 1993). Fortunately, this is not always the case for historic sites, as Brooks *et al.* (2009:41) found magnetometry to be useful for locating features on an historic ploughed site in southern Australia.

Borrowing methods pioneered in Australia by Stanley and colleagues, more recent magnetometry studies have concentrated on mapping Aboriginal hearths using gradiometry (Fanning *et al.* 2009; Moffat *et al.* 2008). While Stanley wanted to determine whether magnetometry was *capable* of mapping archaeological hearth features, recent work has focused on the identification, classification in terms of their magnitude, and management of hearths. A problem in hearth studies is the difficulty of recognising heat-fractured or affected rocks on the ground surface as hearths, as geomorphic disturbances and processes such as erosion can impede their visual identification (Fanning *et al.* 2009; Moffat *et al.* 2008; Wallis *et al.* 2004). The standard method for identifying hearths in Australia has been either to identify them once they have been totally exposed and/or to systematically test areas via excavation to investigate hearth-like features. In response to growing concerns over erosion, and because both traditional custodians and heritage managers want to minimise subsurface disturbances to archaeological sites, alternative methods such as magnetometry and gradiometry are being adopted.

Using visual classifications of surface hearth 'types' identified during a reconnaissance survey in southeast Australia, Fanning *et al.* (2009) focused on a way to relate those types to particular magnetic signatures using a gradiometer. They first categorised hearths as partially exposed, intact, disturbed, scattered or remnant, based on physical observations. In turn, they then used those types to map and classify their magnetic signatures by looking at the differences between the general site's background gradiometer reading and that of each hearth. They demonstrated that the densest concentrations of heat-fractured hearth stones produced the highest gradiometer values, while lower concentrations produced lower values (Fanning *et al.* 2009:21-22). However, the instrument was incorrectly zeroed at each hearth, causing collected readings to be inconsistent and therefore making it difficult to classify hearth signatures. Nevertheless, Fanning *et al.* (2009) made an attempt to use geophysics as a way to investigate site integrity based on magnetic signatures accurately, which led to a better understanding of particular hearth types and assisted in site management practices.

Moffat *et al.* (2008) also attempted to use magnetometry to identify and classify hearths at open sites in northwest Queensland, but found it to be largely ineffectual, possibly as a result of the particular instrumentation and data collection methodology. In this study, a proton precession magnetometer was used rather than gradiometry, and consequently the total magnetic field was measured rather than the local field. As such, background noise negatively affected the data and hearths could not be readily identified. Also, because of time constraints, the survey transects used were broader than desirable given the size of the potential hearth signals, thereby decreasing the spatial resolution and potentially impeding identification. MS could have been used in this study instead of magnetometry, since this instrument is also capable of detecting burnt features. Both the Fanning *et al.* (2009) and Moffat *et al.* (2008) studies demonstrate the importance of selecting the most appropriate geophysical instrumentation and data collection methodology for the research questions being asked and the features being investigated.

Other recent studies have focused on lab-based methods using MS to characterise and understand magnetic anomalies, features and mineralogies, particularly with respect to sediments and culturally enhanced or modified soil layers in rockshelter sites (Keys 2009; Marwick 2005). Other innovative MS studies have attempted to understand archaeological pigments in rock art and sourcing of ochre by looking at magnetic grain sizes and concentrations to detect their mineralogy (e.g. magnetite, maghemite, hematite or goethite) (Milani 2010; Mooney *et al.* 2003). Most recently, MS studies have been used to understand questions concerning the nature of geophysical anomalies themselves (Moffat *et al.* 2010). By combining MS with other environmental parameters involving both induced and remnant magnetisation as well as temperature, these 'archaeomagnetic' studies have demonstrated another means by which geophysics can be applied to Australian archaeology in order to better understand the nature of the archaeology itself, particularly human occupation, ochre sources and burial rituals.

Discussion

A shift from testing the efficacy of geophysical techniques to using them as non-invasive methods to assist in investigations and site interpretation is clearly evident in Australian archaeology. Early studies demonstrated that these techniques could be successfully applied in Australian contexts, but were not developed further until several decades later. The factors driving this research deficiency during the infancy of Australian archaeological geophysics have not previously been considered in depth; here I suggest it may be best explained by a combination of factors.

The perceived cost of geophysical instrumentation was a fundamental issue in the past and remains so in the present. In the 1970s, the cost to purchase a magnetometer ranged from $1600 to $7000 (Connah *et al.* 1976) – today it ranges from $10,000 to $50,000. In the 1970s when cultural heritage legislation and standard practices were only just being developed and implemented (Pearson and Sullivan 1999), the funding available for archaeological research, let alone geophysical studies, was minimal and people were concerned with establishing such basic information as dates for Australian colonisation (e.g. Mulvaney 1975). Coupled with the small number of practitioners in Australia and the vast geographical areas involved, costs for site investigations were quite high. Hence, when Stanley first began his geophysical trials, standard excavation appeared to be a much more cost-effective and reliable means for investigating sites than geophysical exploration. Even today, the costs associated with carrying out a geophysical investigation (purchasing or renting equipment for data collection, in addition to data processing and interpretation, the latter requiring specialist skills) exceeds most project budgets: this is one factor contributing to a continuing low uptake of these methods.

The time required to conduct geophysical surveys was also an important early consideration, though recent improvements in technology have greatly reduced data collection and post-fieldwork data processing times. Survey areas that can be completed in a half-day today could have taken up to three days to survey in the 1970s – clearly an impediment to their early usage if time was constrained (Ranson and Egloff 1988:71). Further, before digitising equipment was readily available, collected data was handwritten and later manually processed. Early data analysis software programs, even when available, did not have the computing power to generate the sophisticated, often three-dimensional, geophysical maps we are accustomed to today. Instead, early maps were typically displayed as trace plots, as this was the easiest way of recording continuous readings, or contour plots. Improvements in data processing eventually led to dot density plotting which, while useful for generating 'archaeologist-friendly' maps, required considerable time to produce (Clark 1996; Gaffney 2008). Contemporary computing software and processing speeds have greatly decreased geophysical project times, thereby contributing to a decrease in relative costs while substantially improving the quality of mapping.

The creation of new archaeology departments in universities and the emergence of the cultural heritage management movement through the 1970s, also meant that the demand for archaeologists in Australia was geared towards conducting basic research and finding people to fill newly-created positions (Smith and Burke 2007:3). The process of developing entirely new academic teaching programs necessitated an emphasis on broad Aboriginal and colonial Australian cultural histories (Colley 2000; Smith and Burke 2007:3-8), rather than a shift towards processual research specialisations as was occurring elsewhere (Binford 1968; Caldwell 1959; Willey and Phillips 1955).

Instrument availability is another reason for the rare uptake of geophysics in Australia, where such equipment is used primarily in commercial, mining projects (where targets are extensive and usually deeply buried) or urban planning projects (where the targets include shallowly buried pipes, mesh and metal), all of which involve the detection of highly visible anomalies. Shallow geophysical instruments suitable for detecting subtle archaeological features are not as widely utilised, or thus available for rental, as deep geophysical techniques suited for mining. Additionally, many geophysical instruments are manufactured overseas and it may take several months after purchase before they are shipped and available for use, a situation exacerbated when there is a strong demand for one particular type of instrument. While there are now more Australian businesses specialising in geophysical equipment sales, they too are constrained by international manufacturing and shipping schedules, as such businesses are distributors, rather than manufacturers, of instruments. This means time is an important factor in instrument availability and perhaps another reason that geophysical methods are not as widely utilised in Australia as elsewhere.

Additional factors, such as the ability to understand geophysical anomalies as culturally-generated phenomena, are likely another reason why these methods have been underutilised in Australian archaeology to date. Most geophysical surveys are large-scale, environmentally-based and involve easily detectable targets. When practitioners used to working under the aforementioned circumstances are engaged to undertake archaeological work, they tend to overlook or misinterpret anthropogenically-generated geophysical anomalies – which are often subtle due to the relative size of the targets – simply because their training and experience is geared more towards geology and physics rather than archaeology. Likewise, most archaeologists have limited experience with geophysical techniques, as they are generally taught as part of geological and environmental science degrees, not social sciences and humanities. Hence, students in archaeology, geology and environmental science rarely have the opportunity to undertake training that would prepare them to engage effectively with their respective colleagues to facilitate successful archaeological geophysical collaborations.

As Gibbs and Gojak (2009:45) pointed out, in order to achieve optimum results, archaeologists require an understanding of the appropriate methodology (e.g. which instrument works best in particular environments), as well as of the limitations and challenges likely to be faced in the specific project area for data acquisition, processing and interpretation; understanding the theory and physics of each method is vital to success. While not all geophysical surveys have been successful in locating buried remains – even where archaeological remains are unmistakably present (Bevan 2006; Gibbs and Gojak 2009; Jordan 2009) – knowledge allows a practitioner to understand why features may not be detectable using particular instrumentation. As described earlier, a lack of understanding of geophysical methods is evident in some work conducted to date on Australian sites, including repeated instrument zeroing for a magnetometry survey (e.g. Fanning *et al.* 2009), surveying too broadly (e.g. McDougall *et al.* 1997; Moffat *et al.* 2008; Ranson and Egloff 1988) or choosing techniques that are less well-suited to specific targets and site conditions, such as using magnetometers on sites that may contain a lot of metal (e.g. Gibbs and Gojak 2009; Hall and Yelf 1993). Additionally, many of the studies published to date have been pilot studies and, as such, demonstrate that geophysics in Australian archaeology is still being utlised primarily as an investigative technique to map sites, rather than as a research tool to help answer questions about human behaviour (Brooks *et al.* 2009; Hall and Yelf 1993; Moffat *et al.* 2008, 2010; Powell 2004; Wallis *et al.* 2008).

Almost all of the Australian studies discussed above reveal difficulties in confidently discerning archaeological features in the absence of excavation, a factor in all remote prospecting. However, limitations in data processing and software (Ranson and Egloff 1988:71), or inexperience in data interpretation, further amplify the problem. In many instances the resulting geophysical maps are limited and difficult to interpret. For instance, most Australian GPR results are presented in two-dimensional reflection profiles and not as amplitude slice maps, whereas both vertical and horizontal images may be better ways of understanding the size and shape of GPR anomalies. Visualisation has been, and will continue to be, an important component of any form of geophysical prospecting, especially as technological advances are made in instrumentation, software and processing. Poorly constructed maps may be a result of early and/or substandard software programs, or the use of programs designed for deep rather than shallow geophysical exploration, leading to a disadvantage in visual representation and data interpretation.

The inherently ancient nature of Australia's landscape is another potential reason for the lack of archaeological geophysical applications here. Climatic changes, especially in the last 50,000 years, have caused significant changes to Australia's landscape that are uniquely different to those experienced elsewhere. As conditions became cooler and drier leading into the Last Glacial Maximum (ca 18,000 ya), wind activity increased and surface water availability and vegetation were reduced, causing the development of dune-building systems and landform erosions across much of the interior (Barrows *et al.* 2002; Bowler 1973; Hesse and McTanish 1999; Hiscock and Wallis 2005). In many places this resulted in either extremely complex stratigraphies or depleted stratigraphic sequences. Further, major sediment building environments, such as volcanos or large river systems (e.g. the Mississippi River in North America), are rare and thus depositional opportunities are limited. Even in cases where sedimentary sequences exist, much of the archaeological material is visible on the surface and thus geophysical techniques are unnecessary. In areas with complex stratigraphy, such as rockshelters, excavation may have been deemed more worthwhile than prospecting methods. Yet, given that Australia's landscape has been significantly altered, one could argue that these are the very reasons geophysics should be used, especially for locating and mapping sites potentially buried as a result of environmental changes.

The ubiquitous seasonal burning of particularly Australia's northern and central landscapes (Bird *et al.* 2008; Bowman 1998; Jones 1969; Yibarbuk *et al.* 2001) is also a consideration in the rate of uptake of geophysical methods. Fires, whether natural or cultural, can produce conditions that lessen the effectiveness of particular geophysical methods, such as magnetics and MS, making it difficult to distinguish cultural from natural magnetic signals produced by burning. While this may be less important in hearth detection (as such fire events create stronger local magnetic signals than landscape burning), interpretation of stratigraphic sequences exhibiting magnetic enhancement may be difficult to interpret, as the presence of charcoal could be a result of either cultural or natural fire events (Herries and Fisher 2010; Hiscock 2008:27).

As apparent from the studies summarised earlier in this paper, all contemporary archaeological geophysical research being conducted in Australia recognises the value of these techniques, and typically mimics the style of studies carried out in Europe and North America during the 1980s and 1990s. Currently, Australian archaeological geophysical projects suffer from a lack of refinement and experience, meaning that applications are routine and basic, a product of the issues discussed above. Of course, studies on how best to collect and process data are always beneficial, yet internationally there has been a noticeable shift towards developing new directions and areas that allow geophysics to address focused research questions, rather than merely functioning as a tool to find buried sites (Conyers and Leckebusch 2010).

Aspinall *et al.* (2008:245) argued that future archaeological prospection studies should emphasise the use of geophysical methods for innovative hypothesis testing, and that prospection alone should not be the ultimate goal. Evidence of this shift can be seen in recent research published in *Archaeological Prospection*. For instance, Lindsay *et al.* (2010) used magnetometry to investigate socio-political change on Late Bronze Age settlements in northwest Armenia and demonstrated that domestic and institutional remains, identified initially through the geophysical data and later by excavations, continued to borrow earlier architectural traditions from the Middle Bronze Age. Further increases in the occurrence and size of large stone fortresses, also detected by magnetometry and later confirmed in excavations, indicated a political shift from nomadic pastoralism to sedentary settlements. By using gradiometry to identify where the majority of the population who built one such fortress actually lived, Lindsey *et al.* (2010:25) were better able to piece together the cultural history of this site.

Jones *et al.* (2010) adopted a combination of geophysics, geochemical and soil micromorphology to explore the functions of a late Neolithic house in northern Scotland. Their magnetometry study was successful in providing a clear boundary for a house structure, with both geochemical and soil micromorphology providing a visible understanding of the house's sedimentary sequence (i.e. original soil layer, floor construction, occupational layer and post-abandonment soil formation) and functionality (i.e. cooking and food preparation, tool manufacture and waste disposal).

Lowe and Fogel's (2010) integration of three geophysical methods (resistance, magnetometry and down-hole MS) using both vertical and horizontal applications with results directing subsequent archaeological excavation, revealed that it is possible to test ideas about the social patterns of ancient fortified village sites in America's Northern Plains using geophysics. Their discovery of multiple ditches and an associated bastion revealed that the inhabitants responded to stresses from nearby neighbours by developing successful defensive strategies.

Finally, Conyers and Leckebusch's (2010) study using GPR to test ideas about *kivas* (large semi-subterranean structures used for communal ceremonies in the American Southwest) led to a substantial re-evaluation of the function and regional political connection of these structures. While finding structures similar to those in the aforementioned studies in Australia is very unlikely, using similar geophysical techniques combined with geochemical analyses and soil micromorphology to look at site functionality could be used on any type of Australian site, whether it be Indigenous or historic. Secondly, vertical and horizontal applications pre-excavation could be used to look at features such as heat-retainer hearths, shell and earth mounds, pits and rockshelters to understand site depositional processes and landscape change, all of which can be used to guide excavation and enhance archaeological interpretations.

Continual technical advances in instrumentation and data processing further increase the potential of archaeological prospection techniques. The advantages conferred by using Real-Time Kinematic GPS with geophysical instruments include a level of spatial control that allows geophysical data to be linked to broader GIS frameworks. Some examples of this include the recent MS research in North America and France, where investigations within trenches and excavation units and visual interpretation of three-dimensional data sets were used to address both archaeological and geophysical questions about features (Dalan 2008; Pétronille *et al.* 2010). Similar studies might profitably be applied to Australian sites, specifically in regards to understanding stratigraphic associations and magnetic features, including hearths, pits and middens. Three-dimensional inversion of resistance profiling (e.g. Papadopoulos *et al.* 2009) and evaluation of multiple coil configurations for EM induction sensors (e.g. Simpson *et al.* 2009) have also demonstrated advances in data processing and interpretation that allow for a better visualisation of archaeological features. One might apply these particular methods to Australian sites to locate features that are specifically of an architectural (i.e. buried structural remains) or geological (i.e. earthen mounds or extinct channels) nature.

Another technical advance can be seen in GPR data collection and processing. Ernenwien and Kvamme (2008) looked at temporal disruptions, including noise and moisture fluctuations, in GPR surveys of large areas and offered solutions in data processing to remedy this. Likewise, Novo *et al.* (2010) developed three-dimensional GPR strategies for targeting anomalies using isosurface rendering over an indoor archaeological site. Similar applications could be applied to Australian sites, specifically historic sites where structural remains and other features, such as roads, gardens, fences or privies, may be important in the reconstruction and interpretation of a site's layout (cf. Gibbs and Gojak 2009; Hall and Yelf 1993; Ranson and Egloff 1988).

Recent studies have also demonstrated how broad-scale geophysics, combined with advanced data processing programs, can be used to investigate archaeological sites. Large-scale, deep-subsurface geophysical instruments are being used on tell sites in the Near East as a way to document archaeological features and stratigraphy in three-dimensions and at much greater depths than is possible with conventional geophysical methods (e.g. Casana *et al.* 2008). Through a combination of low-frequency GPR and electrical resistance tomography (ERT), highly detailed maps revealing architectural plans and monumental buildings in multiple and superimposed stratigraphic sequences can be generated. Large-scale electromagnetic conductivity surveys are also being used to predict site locations in meandering river floodplains in North America, demonstrating that particular areas on the channels may be more probable locations for human occupation (Conyers *et al.* 2008). While such studies may be a long way off in Australian archaeology, they demonstrate the existing potential, particularly with respect to the identification of sites along palaeo-river channels.

Moffat *et al.*'s (2010) article on using a combination of geophysical instruments and environmental magnetic work to understand Holocene burials is the first study in Australia to move beyond basic geophysical data collection and analysis. Here the authors were not only trying to identify burials, but also looking at the physical properties of the geophysical anomalies associated with them using laboratory analyses of magnetics and mineralogy to determine whether findings could be correlated with Indigenous funerary practices. Although this research was a pilot study, the authors demonstrated how geophysical techniques can be used to understand particular burial practices in these Holocene sites – clearly an example of how geophysics can be used to understand past human behaviour.

Moving Forward: Archaeological Geophysics and Landscape in Australia

The discipline of archaeological geophysics is still in its infancy in Australia and, with a few recent exceptions, research applications are often underdeveloped compared to those worldwide. Technological advances in instrumentation elsewhere provide substantial aids for basic data collection and analysis, yet these practices are still limited in Australian archaeology. Undoubtedly one of the main inhibiting factors has been a general lack of familiarity with these methods to date and a corresponding lack of realisation by Australian archaeologists as to how they might profitably beapplied to their own research.

Only in the last decade has there been an increase in systematic geophysical prospection on Australian archaeological sites, probably caused in part by Australian archaeologists developing a greater appreciation through increased exposure (via media including the internet, specialist publications and television programs) to the success of geophysical applications on archaeological sites elsewhere. Perhaps just as importantly, interest has escalated as a result of several university archaeology departments investing in suites of geophysical equipment (e.g. Flinders University, James Cook University, Sydney University, The Australian National University and The University of Queensland). An archaeological prospection short course offered regularly through Flinders University and other short courses, such as those hosted prior to the start of the 2010 Australian Archaeological Association annual conference and taught by invited keynote speaker Prof. Larry Conyers, are now providing qualified archaeologists, as well as students, with opportunities to learn directly from experts about these techniques. Newly established support groups, such as the Archaeological Prospection Group (APG) at the University of Sydney, are further promoting the use of archaeological geophysics in Australia.

If archaeological geophysics can indeed produce primary data with which to study the human past rather than merely being used as a preliminary step to find sites prior to standard excavation and, if we as archaeological geophysicists are to move towards using these techniques to investigate human behaviours in the archaeological landscape, then we might ask how can we achieve this in Australia? I suggest the answer lies at least partially in having a greater emphasis on the landscape in research agendas. Geophysical techniques can map both natural and cultural physical changes at sites. Regardless of whether these changes were large, such as the construction of a monumental earthwork or coastal shell midden, or small, as is the case of a pit or hearth, these modifications were created by people who lived in landscapes and made use of them in multitudes of ways through their social and cultural beliefs, and actions.

For Australian archaeologists, the next step is to determine whether they are ready to develop the skills necessary to conduct geophysical surveys themselves or prefer to team up with colleagues from cognate disciplines, such as geology or geophysics, to better understand Australia's archaeological landscape. Despite their current underutilisation, I believe the trajectory outlined above demonstrates there is potential to train Australian archaeologists in these methods or, perhaps less ambitiously, at least better inform them about how geophysics can be effectively used in their research. The final decade of the twentieth century brought with it the opportunity for archaeologists to become geophysical prospection practitioners. With trial and error, time and knowledge, it has now become a norm in most archaeological research. While it is always important for archaeologists to work in multidisciplinary teams, the fact that geophysical training, albeit limited, is now locally possible, affords the opportunity for significant advances to be made in the field of archaeology. Steps towards realising this in Australia would be to provide more training and short courses geared towards archaeological prospection and to see more published studies of its use in archaeological research.

It is evident that Australian archaeologists have no hesitation in collaborating with colleagues from widely varying disciplinary backgrounds or utilising novel proxies to assist in their studies of, and interpretations about, the past, site formation processes and environmental change. By joining their international counterparts who have embraced geophysics, Australian archaeologists will be better positioned to undertake intra- and intersite analysis of features at sites. Multidisciplinary approaches allow for the assessment and reconstruction of the cultural historical landscape, something usually not possible with standard archaeological approaches. As archaeological geophysics becomes more widespread, and advances in technology and data processing continue to be made, the outcome will be a better understanding of human cultural behaviour in Australian landscapes.

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