Geophysical survey methods and cultural heritage management in Australia

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Abstract

Geophysical survey methods, including ground penetrating radar (GPR), electromagnetic induction, electrical resistivity, magnetic gradiometry and magnetic susceptibility, provide a rapid, non-destructive means for investigating subsurface deposits. Most techniques are based on measuring how signals pass through subsurface deposits. These signals can be magnetic (gradiometry, susceptibility), electrical (resistivity, electromagnetic induction) or electromagnetic (GPR). In Australia, geophysical survey methods have been applied to identify and map the locations of historical archaeological features, and to identify and/or investigate Aboriginal cultural heritage features such as shell middens, earth mounds, hearths and burials. Geophysical survey results can also be used to inform subsurface testing strategies, providing information to assist with selecting areas to target or avoid during archaeological excavation. Geophysical survey methods have so far been underutilised for Australian archaeological projects, despite possessing significant potential to contribute to positive outcomes in the context of cultural heritage management.

Introduction

Geophysical survey methods provide rapid, non-destructive means for investigating subsurface features and deposits. Passive methods, such as magnetic gradiometry, measure existing parameters that can be interpreted to provide information about subsurface features. Active methods, such as ground penetrating radar (GPR), electromagnetic induction (EMI), magnetic susceptibility (MS) and electrical resistivity, measure how induced signals pass through subsurface deposits. These signals can be magnetic (e.g. susceptibility), electrical (e.g. electrical resistivity, electromagnetic induction) or electromagnetic (e.g. GPR). Geophysical survey methods can provide information about both cultural and non-cultural subsurface features and conditions that are relevant to cultural heritage management. This paper describes different geophysical survey methods, and outlines the ways they can, and have been, applied in the fields of archaeology and cultural heritage management, with a particular focus on the Australian context.

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Ground Penetrating Radar (GPR)

GPR uses electromagnetic wave propagation to characterise and map variation in subsurface deposits. The GPR equipment can be set to transmit electromagnetic waves (usually in pulses) at different velocities at a frequency determined by the type of antenna used. The frequency range for most commercially available antennae is 25 MHz–1000 MHz, with different frequencies suited to the investigation of different subsurface depths. The propagation and return rate of the signal varies depending on several factors, including the conductivity and Relative Dielectric Permittivity (RDP) conditions of the ground (see Conyers and Goodman 1997; Olhoeft 1981 for more detail). The returned reflection is collected, sampled and digitised into a reflection trace in the control unit, providing outputs in the form of stacked traces in sequence over the distance travelled (Conyers 2012:25–26). These raw radargrams are typically displayed on screen as the survey is conducted. The relative ease with which the radar penetrates the subsurface deposits forms the basis of the data that are produced.

Dedicated software is used to produce outputs for interpretation. In addition to examining individual vertical radargrams, horizontal slices of interpolated radargrams are sampled at different time-depths to produce plans of the GPR survey results at specific depths, typically referred to as permittivity heat maps or time slices in archaeology (Goodman 1995).

Electromagnetic induction (EMI)

EMI (also known as electromagnetic conductivity) surveys detect and map variation in the ability of subsurface deposits to transmit an electrical current (Clay 2006). Variation in conductivity can relate to the presence of cultural heritage or other relevant features (e.g. archaeological stratigraphy, ground disturbance). EMI surveys for archaeology are usually undertaken using an EM38 device, which measures conductivity to depths of approximately 1.5 m below the ground surface. EM31 measures conductivity for depths between 2–6 m, which is considered more suitable for generating information about landscape features (e.g. Conyers et al. 2008).

EMI devices typically contain a transmitter coil and a receiver coil. The transmitter coil acts as an electromagnet, producing a rapidly oscillating 'primary' magnetic field. This field penetrates the subsurface deposits, inducing eddy currents, which, in turn, elicit a 'secondary' magnetic field. The receiver coil detects the secondary magnetic field, which varies in strength according to the conductivity of the subsurface deposits (Kvamme 2001). Generally, low EMI resistant features (e.g. water-logged fill) are characterised by high conductivity whereas high EMI resistant features (e.g. wall foundations) are characterised by low conductivity.

Electrical resistivity and electrical resistivity tomography

Electrical resistivity involves passing electrical currents between metal probes and measuring how resistant the intervening substrate is to the movement of electricity through it (Somers 2006). Different substrates tend to have different resistivity properties, particularly relating to moisture content, so variation in resistivity may relate to the presence of cultural heritage or other relevant features that disrupt (or enhance) the flow of electrical current (Clark 1996). Survey proceeds by placing sets of probes in contact with the ground and by measuring resistivity between pairs of probes. This is undertaken at regular intervals and the results are mapped to reveal any patterns of variation that are present.

Electrical resistivity tomography expands on this by allowing the investigation of deeper subsurface deposits in 3D via mathematical inversion of resistivity data (Tsokas et al. 2009). It is often used over small selected areas following standard resistivity or other geophysical survey for high-resolution 3D mapping of known subsurface features (e.g. Simyrdanis et al. 2018).

Magnetic gradiometry (magnetometry)

Magnetic gradiometry is a method for measuring and mapping the strength of magnetic fields in the near-surface encountered during survey (Kvamme 2006). In archaeology, the technique is used to detect localised anomalies in the Earth's magnetic field, produced by the presence of anthropogenic materials or features within the subsurface (e.g. bricks, hearths, ditches, pits) that contrast in magnetic signal with that of the surrounding sediment. Anomalies of interest derive from activities such as the firing of material to high temperatures (e.g. clays fired to ~600°C), which produces a thermal-remanent magnetisation (TRM; i.e. a permanent magnetisation) as iron-mineral inclusions cool under influence of the Earth's magnetic field (Butler 1992). A common instrument in magnetic gradiometry is a fluxgate gradiometer, typically composed of two sensors vertically spaced ~1 m apart, with the difference between the two readings reflecting the vertical component of the magnetic field (Kvamme 2001).

Unlike most geophysical survey methods, magnetic gradiometry is a passive technique. It does not involve the application of a stimulus to detect anomalies, simply using localised variations that are detected in the Earth's natural magnetic field. A 1–2 m depth is a practical limit for successful prospection at archaeological sites (Kvamme 2006). This is likely to be shallower for features with more subtle magnetic enhancement.

Magnetic susceptibility (MS)

Another magnetic parameter for use in survey is MS, which refers to the ability of a material to become magnetised while under influence of an external magnetic field (Butler 1992). In archaeology and the geosciences, this is usually a function of the presence, abundance, type and grain size of iron oxide and oxyhydroxide minerals (e.g. magnetite, maghemite, hematite, goethite etc.) within sediments, rocks and anthropogenic materials.

While a number of natural processes can lead to an enhancement of magnetic susceptibility (e.g. pedogenesis and weathering in soils; Clarke 1996), human activities such as burning can produce large changes in MS due to the formation of magnetically strong ferrimagnetic minerals (Herries 2009). Such changes are detectable using survey instruments that apply a localised magnetic field and measure a material's corresponding MS response. Both magnetic gradiometry and magnetic susceptibility results can be depicted in a heat map which can be examined for anomalies of interest.

Geophysical survey and cultural heritage management

An important part of the cultural heritage management process involves obtaining enough information to determine an effective management strategy. This typically involves describing the extent, nature and significance of any cultural heritage that is present in a study area. Background research provides some level of insight into the archaeological potential of an area, including predictions about what kinds of features are likely to be present. These predictions then require testing, sometimes by archaeological survey, but most commonly by archaeological excavation. Archaeological excavation is a destructive technique for investigation. During the investigative phase of cultural heritage management projects, it is therefore appropriate to excavate only a small proportion of the subsurface deposits (i.e. the minimum necessary to generate the required information).

Geophysical survey techniques can investigate subsurface features and deposits without disturbing them. In most cases, the information generated during geophysical survey can contribute to an understanding of the extent, nature and significance of cultural heritage. In addition, the information generated during geophysical survey can be used as a basis for implementing more targetted and effective subsurface testing strategies to maximise the effectiveness of relatively small amounts of archaeological excavation. For example, if geophysical survey reveals an anomalous signal for part of a study area, it may be worth targeting that area for excavation. Alternatively, if a geophysical survey reveals that an area has been disturbed, it may be unnecessary to undertake further investigation. Furthermore, certain landscape features may be associated with more frequent use, so geophysical survey results can assist with identifying such features, such as palaeochannels, which may relate to the distribution of cultural material.

The use of geophysical techniques for archaeological prospection is well-established in some parts of the world (Lowe 2012:71). GPR and magnetic gradiometry, for example, are routinely undertaken for cultural heritage management projects in the UK. The primary reason for the limited adoption of geophysical survey methods in Australia relates to the more subtle nature of many of the cultural heritage features that are common in Australia, and the need for more research into the suitability of various methods to investigate these features. Method development for the detection and study of subtle archaeological traces has progressed more rapidly in recent times due to the increased availability of specialised equipment and experienced practitioners, such as Kelsey Lowe, Ian Moffatt and their colleagues and students, who are testing and refining approaches that are suitable for the Australian context. Published literature about the capabilities of different geophysical survey techniques for investigating a range of archaeological features in different contexts is still emerging in Australia (see below).

Geophysical survey in Australia

Table 1 presents a summary of published applications of geophysical survey for cultural heritage in Australia. Lowe (2012) provides a comprehensive review of the application of geophysical survey techniques in Australia until 2012. For a detailed consideration of studies prior to 2012, please refer directly to Lowe's (2012) paper.

These studies show that geophysical survey methods can be effective for investigating Aboriginal and historical cultural heritage features, depending on the context of the cultural heritage and the methodology employed. Many historical features are made from materials that are easily detectable, such as metal or brick, and often comprise physically substantial features with a shape that is easy to recognise (e.g. wall foundations).

These studies also demonstrate that geophysical survey methods can identify and investigate some Aboriginal cultural heritage features, despite their subtle physical characteristics. Recent studies have established that it is possible to generate information with explanatory potential during detailed investigations of Aboriginal cultural heritage features. This probably reflects advances in technology, as well as an increase in the availability of specialist operators and an increase in interest by Aboriginal communities.

Historical cultural heritage features

A variety of historical cultural heritage features are detectable using geophysical survey techniques. These include:

- Built features, such as wall foundations and floors;
- Drainage and other infrastructure;
- Voids (e.g. wells, mining shafts/tunnels);
- Industrial features (e.g. flues, pipes);
- Landscaping features (e.g. garden beds, paths);
- Rubbish dumps; and
- Areas of concentrated activity.

Identifying burials

Recent burials and/or formal burials can be detected using a variety of geophysical survey methods as they are likely to exhibit some or all of the following characteristics:

- A casket, which may have metal coffin furniture and/or a void;
- Discernible fill (the fill above recent burials is more likely to have a different signal to the surrounding subsurface deposits); and
- Standard orientation, depth and size of cut.

It is possible to detect older, Aboriginal Ancestral remains in less formal burials using GPR, but these typically provide a more subtle signal that may vary with different burial practices. The geomorphological context also determines how visible burials will be on GPR results outputs. For example, Conyers (2016:83) determined that burials are more prominent in GPR results outputs when they are situated within aeolian dunes compared to the interdune area.

Aboriginal Ancestral remains can be washed into an area along with fluvial sediments. In this context, it is unlikely that isolated elements would be detectable using geophysical techniques because the areas of potential signal variation would be very small. If the burial is a cremation, it is possible that other techniques (e.g. magnetic gradiometry) could identify the presence of burnt material, including ash.

Identifying hearths

Different types of hearths have different potential for detection using geophysical survey techniques. GPR can detect hearths with solid and/or dense components, such as heat-retainer hearths and substantial baked-sediment hearths/oven pits (e.g. Conyers 2012:155).

Magnetometry also has potential for detecting burnt material. For example, Fanning et al. (2009) used magnetic gradiometry to investigate hearths in northwestern New South Wales. They determined that hearths in relatively good condition can be detected easily using this method.

Studying shell middens

Shell midden matrices typically have vastly different properties to their surrounding sediment, making them a good candidate for geophysical survey techniques. GPR can be used to identify the former ground surface at the base of shell middens, and to determine variation in the internal structure of shell middens, which sometimes relates to successive episodes of midden deposition (e.g. Conyers 2016:117).

GPR can also be used to determine the lateral and vertical extent of shell middens, from which the volume of shell matrix can be estimated (Kenady et al. 2018a, 2018b). Kenady et al. (2018a) determined that GPR creates more accurate volume estimates and 3D models than electrical resistivity, but not in high-moisture conditions where it is the other way around. These techniques are particularly pertinent to cultural heritage mitigation assessments in the face of expected global sea-level rise.

Magnetic susceptibility can contribute to the identification of multiple episodes of deposition for coastal shell middens that otherwise seem to have been deposited 'instantaneously' (e.g. Rosendahl et al. 2014). The explanatory potential here is substantial: it is possible to use non-destructive geophysical survey methods to determine shell midden characteristics that relate to past behaviours and patterns of land-use—for example, whether a midden represents the repeated use of a locality, or has accumulated as a result of large-scale, short-term resource consumption, which may occur when groups of people assemble.

Detecting non-cultural features of relevance to cultural heritage management

Non-cultural subsurface features can also be informative for cultural heritage management. For example, GPR has been used to map archaeologically important cave systems in Europe (e.g. Čeru et al 2017, 2018; Gosar 2012). It has also proven successful for mapping remnant cave sediments, and for providing new data on the location of unknown cave systems—particularly in karst landscapes (e.g. Herries et al. 2018). There is potential for GPR to be used to map Australian cave systems as part of archaeological investigations.

It is also possible to determine former waterway alignments using geophysical survey methods. The alignment of creeks and rivers changes over time, and former alignments (palaeochannels) are important features for understanding the distribution of archaeological materials, particularly in Australia where proximity to water often correlates with greater evidence for land-use—including higher lithic densities (e.g. Canning 2003:255; White and McDonald 2010). GPR can detect palaeochannels (e.g. Figure 1), allowing their alignment to be mapped and incorporated into archaeological investigation and interpretation.

It can be useful to know the locations of former waterways when planning an archaeological investigation. For example, it may be best to avoid excavating into the middle of a former waterway, due to the lower potential for cultural material to be present. Conversely, areas close to waterways are considered to have high potential for the presence of Aboriginal cultural heritage, and areas close to former alignments may be more likely to yield older archaeological traces. Regardless of the specific aims of the investigation, information about the location of former waterways within a study area is likely to be important for identifying and interpreting the cultural heritage.

Discussion and conclusion

Geophysical survey methods in Australia are underutilised, despite their significant potential to inform cultural heritage management projects. These methods are non-destructive, relatively rapid, and well-suited to the goals of cultural heritage management. They

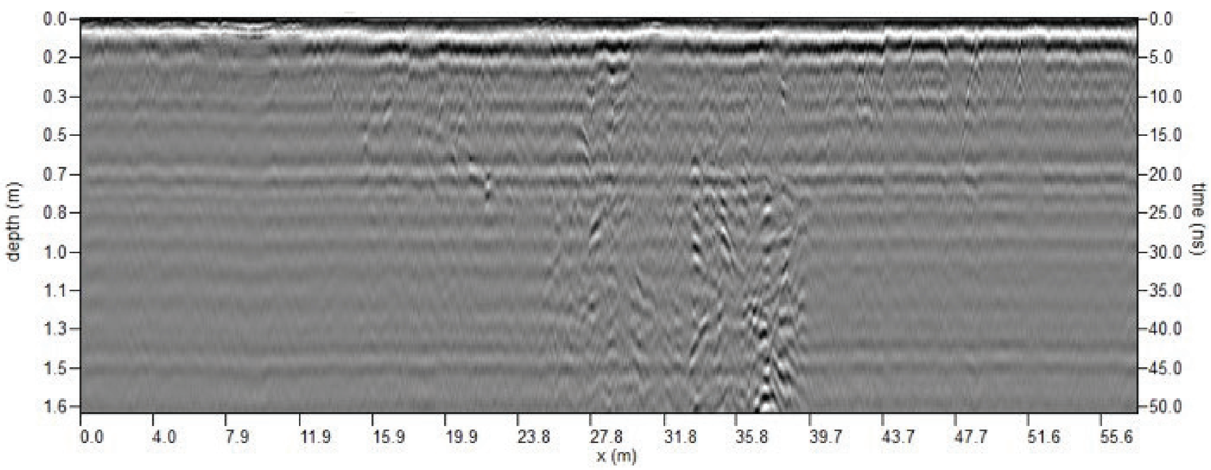

Figure 1. Radargram image showing the former waterway in cross-section (approximately 'v'-shaped feature)

can provide information about subsurface features and deposits prior to, or as an alternative to, archaeological excavation, depending on the goals of the project. Non-destructive investigation of Aboriginal cultural heritage can also also align well with Traditional Owner aspirations, and may provide a cost-effective method for determining the nature and extent of some features without causing them further harm. Geophysical survey data can generate information about subsurface cultural heritage features, or past landscapes, that may be relevant to the distribution and interpretation of cultural heritage (e.g. palaeochannel locations).

Geophysical survey methods can investigate a variety of Aboriginal cultural heritage and historical features that are common in Australia. It is often useful to use a combination of techniques, and/or to integrate the results of geophysical survey with the results of traditional archaeological and geoarchaeological investigation. Additional data pertaining to the efficacy of different geophysical survey methods for detecting and generating information about subsurface cultural heritage features in a variety of contexts would improve cultural heritage management outcomes in Australia substantially.

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Site	Location	Context	Technique	Application	Key outcomes	Reference
Stuarts Point, Clybucca 3, Bass Point midden and Nobby's Creek rockshelter	NSW	Various	Magnetometry	Hearths, shell middens and rockshelters	<u>Target feature detection</u>: Yes (hearths and shell middens only)	Connah et al. 1976
N/A	N/A	Experimental	Magnetometry	Hearths	<u>Target feature detection</u>: Yes	Stanley & Green 1976
Parish cemetery and surrounds	Forster, NSW	Coastal (estuarine)	Magnetometry	Burials (Aboriginal, historical)	<u>Target feature detection</u>: Yes • Comparison of known and un-known grave locations to help diagnose magnetic anomalies • Highlights issues of underlying magnetically-strong volcanics biasing the results • Linked with lab-based magnetic susceptibility of the soil profile to investigate the suitability of magnetometry	Stanley & Connah 1977
DP/2 (75271/013), DP/4 (75271/184)	Nyah Forest, VIC	Alluvial plain	Magnetometry	Earth mounds	<u>Target feature detection</u>: Yes, but need for further study is identified	Elliott 1980
HMS Pandora, Sydney Cove and Point Cloates shipwrecks	QLD, TAS, WA	Marine	Airborne magnetometry	Shipwrecks (at sea)	<u>Target feature detection</u>: Yes	Henderson 1980
Bunbury Whalers and Carbet Castle shipwrecks	Bunbury, WA	Coastal (dune)	Magnetometry	Shipwrecks (on land)	<u>Target feature detection</u>: Yes	Cushnahan & Staniforth 1982
Bunda I	Bunda Lake, NSW	Lacustrine	Magnetometry	Hearths	<u>Target feature detection</u>: Yes	Bonhomme & Stanley 1985

Table 1. Summary of published applications of geophysical survey for cultural heritage in Australia. For papers that do not provide information about the subsurface/sedimentary context, this information has been derived from geological mapping (Geosciences Australia 2019)

Site	Location	Context	Technique	Application	Key outcomes	Reference
Wybalenna Cemetery (Flinders Island) and Port Arthur Historic site	TAS	Coastal	Electrical resistivity	Burials (Aboriginal, historical) and historical site features	<u>Target feature detection</u>: Yes	Ranson & Egloff 1988
Tower Mill	Brisbane, QLD	Urban	GPR, magnetometry	Historical site features	<u>Target feature detection</u>: Yes	Hall & Yelf 1993
Rottnest Island Aboriginal Cemetery	WA	Coastal	GPR	Burials (Aboriginal, historical)	<u>Target feature detection</u>: Yes (magnetometry only)	Randolph et al. 1994
Ebenezer Mission Cemetery	Antwerp, VIC	Alluvial plain	GPR, magnetometry	Burials (Aboriginal, historical)	<u>Target feature detection</u>: Yes (magnetometry only)	Brown et al. 2002 (referring to an unpublished report)
West End Cemetery	Townsville, QLD	Alluvial plain	Electrical resistivity, GPR, magnetometry	Burials (historical)	<u>Target feature detection</u>: Yes (magnetometry only). • Detection due to presence of metal grave markers	Stanger & Roe 2007
Willandra Lakes footprint site	NSW	Lacustrine (clay hardpan)	GPR	Stratigraphic (determining the extent of a clay hardpan known to bear fossil trackways)	<u>Target feature detection</u>: Yes	Webb 2007 (referring to an unpublished report; see also Westaway et al. 2013)
N/A	Northwest QLD	N/A	EMI, magnetometry	Hearths, shell middens and burials	<u>Target feature detection</u>: Burials only	Moffat et al. 2008
Hack's Point burial complex	Coorong, SA	Coastal (dune)	EMI, magnetometry	Stratigraphic (identifying undisturbed ground for the reburial of repatriated remains within traditional burial places)	<u>Target feature detection</u>: Yes	Wallis et al. 2008
Bean's Parsonage site	Gippsland, VIC	Alluvial plain	Magnetometry	Stratigraphic (determining ploughzone disturbance on a historical site)	<u>Target feature detection</u>: Yes	Brooks et al. 2009

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Site	Location	Context	Technique	Application	Key outcomes	Reference
Rutherfords Creek valley floor	Paroo-Darling National Park, NSW	Alluvial plain	Magnetometry	Hearths	Target feature detection: Yes	Fanning et al. 2009
Hereford House, Dr H. J. Foley Rest Park	Sydney, NSW	Urban	Electrical resistivity, GPR, magnetometry,	Historical site features	Target feature detection: Yes (GPR and electrical resistivity only) • The urban setting with multiple metal sources complicated magnetometry results	Gibbs & Gojak 2009
Hack's Point burial complex	Coorong, SA	Coastal (dune)	EMI, magnetometry, magnetic susceptibility, GPR	Burials (Aboriginal)	Target feature detection: Yes (magnetometry and magnetic susceptibility only) • Complex stratigraphy produced several GPR anomalies not related to burials • Burning and/or ochre use in funerary practices hypothesised to enhance the magnetic signal leading to positive feature detection	Moffat et al. 2010
Potential site of 'Mokare's' grave	Albany, WA	Urban	GPR	Stratigraphic (determining the extent of anthropogenic fill for ruling out the presence of burials)	Target feature detection: Yes	Bladon et al. 2011
Mapoon Mission Cemetery	Cape York, QLD	Coastal (dune)	GPR	Burials (Aboriginal, historical)	Target feature detection: Yes	Sutton et al. 2013
Kiacatoo	Lachlan River, NSW	Alluvial plain (palaeochannel levee)	GPR	Burials (Aboriginal)	Target feature detection: Yes	Kemp et al. 2014
Madjedbebe	Arnhem Land, WA	Rockshelter (sandstone)	GPR	Burials (Aboriginal)	Target feature detection: Yes	Lowe et al. 2014

Table 1 continued. Summary of published applications of geophysical survey for cultural heritage in Australia. For papers that do not provide information about the subsurface/sedimentary context, this information has been derived from geological mapping (Geosciences Australia 2019)

Site	Location	Context	Technique	Application	Key outcomes	Reference
Thundiy and experimental midden sites	Bentinck Island, QLD	Coastal and experimental	GPR, electrical resistivity	Shell middens	<u>Target feature detection</u>: Yes • Obtained volume estimates for shell matrix deposits	Kenady et al. 2018a; 2018b
Boralga Native Mounted Police Camp	Cape York, QLD	Alluvial plain	GPR, magnetometry	Historical site features ('ant bed' earthen floors)	<u>Target feature detection</u>: Yes (GPR only) • Magnetometry detected refuse areas but not the floors	Lowe et al. 2018
The 'Crowie' paddle steamer barge wreck	Murray River, SA	Riverine	3D electrical resistivity tomography, multibeam and sidescan sonar	Shipwrecks	<u>Target feature detection</u>: Yes • Included the underwater mapping of a submerged barge and material below the riverbed • The results of 3D modelling were compared with historic photographs	Roberts et al. 2016; Simyrdanis et al. 2018; 2019
Mapoon	Cape York, QLD	Coastal (dune)	GPR, magnetometry	Earth mounds containing burials	<u>Target feature detection</u>: Yes • Some mounds show evidence of pre-construction burning, large internal objects, and complex stratigraphic layering (suggesting multiple building episodes) • Coffin and traditional burials were identified within the mounds	Conyers et al. 2019a; 2019b; St Peirre et al. 2019

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