THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Understanding Australia's Cultural History Through Archaeological Geophysics

Kelsey M. Lowe
BA, Minnesota State University Moorhead, 2003
MA, University of Mississippi, 2005

A thesis submitted for the degree of Doctor of Philosophy at
The University of Queensland in 2014
School of Geography, Planning and Environmental Management

Abstract

The aim of this thesis is to develop and apply geophysical methods for Australian archaeology. The methods focus on magnetic susceptibility and ground-penetrating radar (GPR). The techniques are contextualised through application to the following four key archaeological questions: 1) Can magnetic susceptibility assist in resolving questions surrounding the potential downward movement of stone artefacts in rockshelter deposits? 2) Is human occupation persistent through the changing climatic regime associated with the last glacial maximum (LGM) at a Pleistocene-aged rockshelter in interior Australia? 3) How might we identify burials in a geologically complex rockshelter deposit? 4) How might magnetic susceptibility contribute to knowledge about the formation of 'archaeologically instantaneous' shell matrix sites?

In exploring these questions, research was conducted at two rockshelters in northern Australia and on three shell mounds in the Gulf of Carpentaria, Australia. Magnetic susceptibility studies were undertaken at Gledswood Shelter 1 (GS1), a rockshelter occupied at ca 38,000 BP, to understand its history and formation processes. An experimental burning program using off-site samples was conducted to confirm that magnetically enhanced sediments in the cultural deposits were the direct result of anthropogenic burning rather than natural fires, pedogenesis or weathering. This change coincides with the level at which stone artefacts appear in the sedimentary sequence, indicating that they are *in situ* and have not moved down from higher layers above. Demonstrating that an increase in magnetic susceptibility is associated with human occupation is a crucial development in Australian archaeology. This will provide an opportunity to link sediments and artefacts—and this is critical to comprehending the timing of initial occupation of the continent.

Magnetic susceptibility data combined with micromorphology and geoarchaeological data also revealed that occupation was continuous through the LGM at GS1, without any abandonment of the site. GS1 is situated in a region that has been characterised as a potential corridor for early colonists moving into the arid interior. The appearance of stone artefacts in the deposits corresponding with an increase in magnetic susceptibility as well as clay and charcoal coatings on quartz grains in the Pleistocene units in thin section, indicate that the site was occupied through this period, thereby implying that water was at least locally available. Despite the absence of any obvious permanent water sources, water availability at the site is reliant on summer rainfall. This suggests that the monsoons driven by the Coral Sea off the northeast Australian coastline may have been active during this time. This has important implications for understanding climatic conditions during that period, and allows one to infer that water must have been available regionally for people to have maintained their use of the site.

GPR carried out in advance of archaeological excavations at Madjedbebe, a sandstone rockshelter in western Arnhem Land, identified numerous subsurface rocks (large cobbles); excavation subsequently revealed these were associated with human burials. Post-excavation, geographical information systems (GIS) and statistical analysis clarified that a relationship between rocks and human burials exists. Graves were dug within the shelter and rocks were placed on the individuals before being covered. The rocks were the source of the strong GPR reflections and insights into burial practices derived from ethnographic sources further assisted with the geophysical interpretation. Application of this methodology provides an opportunity to test a way to identify unmarked burials at other rockshelter sites, and a useful management tool for Indigenous communities and heritage practitioners since it is non-invasive and non-destructive.

The third group of sites is the shell mounds located in the Gulf of Carpentaria. Despite archaeological evidence including radiocarbon dates suggesting a single episode of deposition at these sites, the magnetic susceptibility combined with a range of sedimentary and archaeological analyses revealed that these shell mounds were repeatedly occupied. Results also demonstrated that magnetic signatures were related to cultural formation processes most likely from anthropogenic burning, rather than natural processes. These correlations between geophysical indicators and artefactual material suggest that the site retain a high degree of stratigraphic integrity. This has important implications for studies of other shell mounds sites, especially where the limitations of radiocarbon dating may mask multiple depositional events.

In summary, this thesis demonstrates that both magnetic susceptibility and GPR studies can be valuable tools in deciphering key archaeological questions in the Australian landscape. The most important findings relate to the ability of magnetic susceptibility signals to clearly define levels at which humans first appear in the archaeological record. This will allow a major progress in determining the timing and dispersion of human settlements for Australian sites.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the General Award Rules of The University of Queensland, immediately made available for research and study in accordance with the *Copyright Act 1968*.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis.

Publications during candidature

Peer-reviewed papers:

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84.

Lowe, K. M., L. A. Wallis, C. Pardoe, B. Marwick, C. Clarkson, T. Manne, M. A. Smith and R. Fullagar 2014 Ground-penetrating radar and burial practices in Western Arnhem Land, Australia. *Archaeology in Oceania* 49:148–157.

Rosendahl, D., K. M. Lowe, L. A. Wallis and S. Ulm 2014 Integrating geoarchaeology and magnetic susceptibility at three shell mounds: A pilot study from the Gulf of Carpentaria, Australia. *Journal of Archaeological Science* 49:21–32.

Conference Abstracts:

Lowe, K. M. (Upcoming 2014). Australian Archaeological Association (AAA) Annual Conference. Session Co-Convener with A. S. Fogel: Remotely sensed landscapes in 21st archaeology), Cairns, Australia, December.

Lowe, K. M., A. Fogel, B. Barker and L. Lamb (Upcoming 2014) Public archaeology working together with archaeological research: A multiple method geophysical survey of an early historic period inn at Drayton, QUEENSLAND. Paper presented at the AAA Annual Conference, Cairns, Australia, December.

Kenady, S., K. M. Lowe, S. Ulm and P. Ridd (Upcoming 2014) Multi-method geophysical survey of large shell matrix sites: A case study from Thundiy, Bentinck Island, Gulf of Carpentaria. Paper presented at the AAA Annual Conference, Cairns, Australia, December.

Wallis, L. A., K. M. Lowe, R. Popelka-Filcoff, J. Bennett, C. St George, K. Fitzsimmons, C. Lenehan, A. Watchman, C. Wight and J. Matthews 2014 Ochre fragments through the late Quaternary at Gledswood Shelter 1, northwest Queensland. Paper presented at the Australasian Quaternary Association (AQUA) Annual Conference, Mildura, Australia.

Lowe, K. M., L. A. Wallis, C. Pardoe, B. Marwick, C. Clarkson, T. Manne, M. Smith and R. Fullagar 2013 Ground-penetrating radar and burial practices in western Arnhem Land. Paper presented at the AAA Annual Conference, Coffs Harbor, Australia, July.

Wallis, L. A., C. Pardoe, T. Manne, K. M. Lowe, J. Matthews, C. Clarkson, B. Marwick, R. Fullagar and M. Smith 2013 Much more than just an old site: Human remains from the 2012 excavations at Madjedbebe, western Arnhem Land, Australia. Paper presented at the AAA Annual Conference, Coffs Harbor, Australia, December.

Fogel, A., D. Rosendahl, J. Budby, J. Budby, K. M. Lowe and L. A. Wallis 2013 Mapping the invisible: Using magnetic susceptibility to assist in hearth salvage and site mapping on a mine site in central Queensland. Paper presented at the AAA Annual Conference, Coffs Harbor, Australia, December.

Clarkson, C., M. Smith, R. Fullagar, B. Marwick, T. Manne, L. A. Wallis, Z. Jacobs, R. Roberts, K. M. Lowe, A. Florin, X. Carah, C. Pardoe and E. Hayes 2013 Report on new research at Madjedbebe (Malakunanja II). Paper presented at the AAA Annual Conference, Coffs Harbor, Australia, December.

Lowe, K. M. and L. A. Wallis 2013 Understanding magnetically enhanced sediments in a sandstone rockshelter in northern Australia. Poster presented at the Society of American Archaeology (SAA) Annual Conference. Honolulu, Hawaii, USA, April.

Rosendahl, D., K. M. Lowe, L. A. Wallis and S. Ulm 2012 Magnetic mounds: An analysis of magnetically enhanced sediments in three shell mounds on Mornington Island, northwest Queensland. Paper presented at the AAA Annual Conference, Wollongong, Australia, December.

Lowe, K. M. AAA Annual Conference. Session Convener: Machines That Go Bing 2011. Toowoomba, Australia, December.

Lowe, K. M., L. A. Wallis and B. Keys 2011 Earth, wind and fire: A preliminary study using interdisciplinary methods at Gledswood Shelter 1, north Queensland. Paper presented at the AAA Annual Conference, Toowoomba, Australia, December.

Publications included in this thesis

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84. – incorporated as Chapter 2.

Contributor	Statement of contribution
Kelsey M. Lowe (Candidate)	Designed research and wrote paper (100%)

Lowe, K. M., J. Shulmeister, J. A. Feinberg, T. Manne, L. A. Wallis and K. Welsh Using soil magnetic properties to determine the level of onset of human settlement at Australian archaeological sites. Submitted to *Geoarchaeology* in January 2014, revised and resubmitted in May 2014. – incorporated as Chapter 3.

Contributor	Statement of contribution
Kelsey M. Lowe (Candidate)	Designed the research, performed all laboratory work and analysis (100%) Wrote the paper (75%)
James Shulmeister	Wrote and edited paper (10%)
Joshua A. Feinberg	Assisted with the soil magnetic analysis and interpretation (100%)
Tiina Manne	Wrote and edited paper (5%)
Lynley A. Wallis	Collected archaeological samples (100%) Wrote and edited the paper (5%)
Kevin Welsh	Wrote and edited the paper (5%)

Lowe, K. M., S. Mentzer, L. A. Wallis and J. Shulmeister The late Quaternary in interior northeastern Australia: Human occupation through the last glacial maximum. Submitted to *Quaternary Science Reviews* in July 2014. – incorporated as Chapter 4.

Contributor	Statement of contribution
Kelsey M. Lowe (Candidate)	Designed research, performed all magnetic susceptibility and mineralogy analysis (90%) Wrote the paper (70%)
Susan Mentzer	Carried out micromorphology analysis (100%) Wrote and edited paper (10%)
Lynley A. Wallis	Organised and designed the study (10%) Wrote and edited paper (10%)
James Shulmeister	Wrote and edited paper (10%)

Lowe, K. M., L. A. Wallis, C. Pardoe, B. Marwick, C. Clarkson, T. Manne, M. A. Smith and R. Fullagar 2014 Ground-penetrating radar and burial practices in Western Arnhem Land, Australia. *Archaeology in Oceania* 49:148–157. – incorporated as Chapter 5.

Contributor	Statement of contribution
Kelsey M. Lowe (Candidate)	Designed research, collected and processed GPR data (100%) Wrote the paper (60%)
Lynley A. Wallis	Wrote and edited paper (20%)
Colin Pardoe	Wrote and edited paper (10%)
Ben Marwick	Statistical analysis of data in Figure 5.8 (100%) Wrote and edited paper (2%)
Chris Clarkson	Wrote and edited paper (1%)
Tiina Manne	Wrote and edited paper (5%)
Mike A. Smith	Wrote and edited paper (1%)
Richard Fullagar	Wrote and edited paper (1%)

Rosendahl, D., K. M. Lowe, L. A. Wallis and S. Ulm 2014 Integrating geoarchaeology and magnetic susceptibility at three shell mounds: A pilot study from the Gulf of Carpentaria, Australia. *Journal of Archaeological Science* 49:21–32. – incorporated as Chapter 6.

Contributor	Statement of contribution
Dan Rosendahl	Designed research, performed components of lab analysis (50%) Wrote the paper (45%)
Kelsey M. Lowe (Candidate)	Carried out soil magnetics laboratory work and analyses, processed the data (50%) Wrote and edited paper (40%)
Lynley A. Wallis	Wrote and edited paper (10%)
Sean Ulm	Wrote and edited paper (5%)

Contributions by others to the thesis

Lynley A. Wallis, James Shulmeister and Tiina Manne provided supervisory assistance which included the discussion of ideas and research design, editing of text and revisions for this thesis, as well as inputs and advice regarding grant applications relevant to the research.

Susan Mentzer (Institute for Archaeological Sciences, University of Tübingen and School of Anthropology, The University of Arizona) carried out the micromorphology analysis and results at Gledswood Shelter 1.

Lynley A. Wallis (School of Geography, Planning and Environmental Management, The University of Queensland, Department of Archaeology, Flinders University and Wallis Heritage Consulting), Jacqueline Matthews (University of Western Australia and Wallis Heritage Consulting) and Claire St George (Wallis Heritage Consulting) completed the stone artefact analysis at Gledswood Shelter 1.

Josh Feinberg and Mike Jackson (Institute of Rock Magnetism, University of Minnesota) provided assistance with the mineral magnetic interpretation.

David Appleton (School of Agriculture and Food Science at The University of Queensland) carried out the processing of phosphorous samples.

Statement of parts of the thesis submitted to qualify for the award of another degree

None

Acknowledgements

"There is a magnet in your heart that will attract true friends. That magnet is unselfishness, thinking of others first. When you learn to live for others, they will live for you." – Paramahansa Yogananda

I saw this quote early on in my PhD on the Quotable Quotes from a Coffee News monthly flyer. I thought how appropriate it was when I first glanced at it and saw the word magnet. The primary focus of this thesis research is the use of magnetics or mineral magnetics to understand human behaviour. Here, magnetics were used to scientifically understand people's relationship with the environment over time by understanding the mechanisms for causing magnetic changes in the archaeological record and thus, a sites formation process. Yet, interestingly the term magnetics can also be used subjectively, as a metaphor for describing the relationships people have with one another. Either we attract or we repel. Sometimes we may forget how unique it is to find people who are equally attracted to you, not physically but mentally in terms of research interests and ideas. This leads into another important notion, the idea of synergy, which in some ways is analogous with magnetics since both work with interactions. Synergistic relationships develop as a means of collaborating with similar-minded people in the hope of producing something inspiring and notable. They share their past knowledge and experiences with one another, so that either one can learn from the other, and in return achieve a level of success unknown to them beforehand. Encompassing good and positive team members and motivation are key components of this synergy and attraction. As part of this thesis journey, a 'magnetic attraction' transpired in many forms. It was small in the beginning but grew over time. It includes those people who learned to not only work with me on a collegiate basis but also who became important friends and mentors. For that, I would like to take the time to express my gratitude towards them.

First, I would like to thank my supervisors Lynley Wallis, Jamie Shulmeister and Tiina Manne, for your invaluable support and advice throughout this PhD. Without your input this thesis would not have been possible. I would like to give a special thanks to Lynley Wallis who took a chance on me back in 2009 at the Australian Archaeological Association Conference in Adelaide for agreeing to work with me and finding a way for it to happen.

I have been fortunate to have been surrounded by a number of great people, many who were postgraduate students such as myself, as well as a few others who I met along the way. These include Birgitta Stephenson, Amy Wood, Lydia McKenzie, Ezgi Unal-Amir, Missaka Hettiarachchi, Nathan Wright, Emma Oliver (and Olive), Nivea Siqueira, Cíntia Angelieri, Martina Di Fonzo, Payal Bal, Jessica Thompson, and finally my writing group friends Serena Love and Michael Ostling. I would also like to acknowledge my office mates, as you have been great colleagues and friends: Heidi Pitman, Melissa Bruton, Alvaro Salazar and especially Saori Miyake and Chrystal Mantyka-Pringle. In particular, I would like to thank Dan Rosendahl and Cemre Ustankaya: Dan for being a good friend when I first arrived and willing to team up from the get-go and Cemre for your friendship and assistance throughout this PhD. I would also like to thank Emilija Nicolosi and Michael Tobe, the lab managers from the UQ Social Science and Geography, Planning and Environmental Management (GPEM) for their assistance over the last three years.

As customary in Australia, I would also like to acknowledge the traditional owners of the country I was allowed to conduct research in. This includes the Woolgar Valley Aboriginal Corporation for interior Queensland, the Gundjeihmi Aboriginal Corporation (GAC) and the Mirarr who are the Kakadu traditional owners for the Northern Territory, and the Lardil, Kaiadilt, Yangkaal and Gangalidda traditional owners of the Wellesley Islands.

My research was funded by the University of Queensland, International Postgraduate Research Scholarship and Centennial Scholarship, a Graduate School International Travel Award, and an Institute of Rock Magnetism, University of Minnesota Visiting Research Fellowship. Additional funding support includes the Australian Research Council (ARC) Discover Projects (projects numbers DP 110102864, DP0663047 and DP120103179).

A big thanks goes out to my family, my parents Diane and Steve (Evil Step Father) Silkett, and my dad, Dan Lowe, my in-laws Deanne Fogel, and Dave and Leia Fogel, my Aunt Alene Lowe-Korngable, Donna Olson (Grandma D) and the late Ralph Fogel for your generosity and support, particularly Grandma D for sharing your love of history. I also want to thank my dear friends Nicole Smith and Lezlie Johnson, and my brother Philip Lowe, who too shares the same dreams as I, whether it is to conquer the world or to open a cupcake shop. You have always been sympathetic and understanding of my life goals. And lastly, I want to acknowledge my two twin nieces, Willow Ryanne and Winter Rose Fogel, who entered this world during my last six months of thesis writing. Someday we will meet and as you grow up, I will tell you all about the wonderful stories of digging in the dirt, so that you may aspire to follow in the footsteps of your aunty.

I would also like to acknowledge my archaeology colleagues, Jessica Kowalski and Barbara Hester. I want to thank you Jessica for being a great friend in and out of archaeology. I will never forget our archaeology adventures, digging on Parchman’s Mound A and Modest Mouse, when our careers in archaeology were just beginning. I also want to acknowledge the deceased Barbara Hester, who became a great friend and colleague during my time in coastal Mississippi. You made me a better person by showing me the importance of public archaeology and you taught me that patience and friendship can come with any age.

As I wrap this section up, I realise it would not be complete without an acknowledgement to my first archaeology advisors and mentors, Dr Rinita Dalan and Dr Mike Michlovic and graduate advisor Dr. Jay K. Johnson, Richard Weinstein and John Connoway. All of you provided an incredible opportunity to learn about archaeology, theory and geophysical prospection. Specifically I want thank Rinita for teaching me everything about soils, geophysics – particularly soil magnetics and geoarchaeology. Your advice and continuing support has been crucial in my development as an archaeologist, and for that I am grateful.

Lastly, there is Aaron Fogel, my husband who has tolerated my desire and need to go back to school, and has continually supported my dreams. Without you, this PhD journal may not have been possible. And there is Othello.

Keywords

Australian archaeology, rockshelters, shell mounds, Pleistocene, Holocene, magnetic susceptibility, environmental magnetism, ground-penetrating radar, geoarchaeology, palaeoclimate, site formation processes, northern Australia

Australian and New Zealand Standard Research Classifications (ANZSRC)

212101 Archaeology: 60%

040404 Geophysics: 30%

050503 Soil Science: 10%

Fields of Research (FoR) Classification

2101 Archaeology: 60%

0404 Geophysics: 30%

0503 Soil Science: 10%

TABLE OF CONTENTS

CHAPTER 7

APPPENDIX A

APPPENDIX B

APPPENDIX C

APPPENDIX D

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ARM	anhysteretic remanent magnetisation
asl	average sea level
BP	Before Present
°C	degree Celsius
C	clay
C14	Radiocarbon dating
$CaCO_3$	calcite
cc	cubic centimetre
cmbs	centimetres below surface
CS	coarse sand
DEM	digital elevation model
EM	electromagnetic conductivity
EMI	electromagnetic induction
ENSO	El Niño/Southern Oscillation
EP	effective precipitation
ERT	electrical resistance tomography
$Fe_2O_3$0	maghemite
Fe_3O_4	magnetite
GIS	geographic information systems
GPR	ground-penetrating radar
GS1	Gledswood Shelter 1
α-FeOOH	goethite
αFe_2O_3	hematite
IP	in-Phase
IRM	Institute of Rock Magnetism
K	volume susceptibility
K	Kelvin
ka	thousand years
LGM	last glacial maximum
LOI	loss on ignition
MD	multidomain
Ma	million years
ml	millilitre
mm	millimetre
MNI	minimum number of individuals
mS	millisiemens
MS	medium sand
mT	millitesla
nS	nanoseconds

nT	nanoTeslas
NT	Northern Territory
OIL	oblique incident light
OSL	optical stimulated luminescence
P	phosphorous
ppt	parts per thousand
PSD	pseudo-single domain
Q	quadrature
Queensland	Queensland
RDP	relative dielectric permittivity
SD	single domain
SEM	scanning electron microscopy
Si	silt
SiO_2	quartz
SIRM	saturation isothermal remanent magnetisation
SP	superparamagnetic
SU	stratigraphic unit
T	tesla
TL	thermoluminescence
TP	test pit
µm	microns
UQ	The University of Queensland
VFS	very fine sand
VSM	vibrating sample magnetometer
χ	low-field susceptibility
χfd	frequency dependence of susceptibility
χp	paramagnetic
XRD	x-ray diffraction
XU	Excavation unit (or spit)

CHAPTER 1

INTRODUCTION

1.1 Background

Evidence of past human activities has been largely studied using traditional archaeological methods of excavation and analysis of recovered remains. While these methods aid in the interpretation of sites, technological advances using non-traditional methods such as geophysics, have more recently allowed for a wider understanding of archaeological site settings, especially as they relate to landscapes (Anschuetz et al. 2001; Campana and Piro 2009). Although not as commonly used as in Europe or North America, there has been a growing interest in broadening the use of geophysical techniques in Australian archaeology (e.g. Gibbs and Gojak 2009; Moffat et al. 2008; Wallis et al. 2008).

Geophysics is the examination of the earth's physical properties through the use of non-invasive technologies such as electrical resistance, electromagnetic conductivity, ground-penetrating radar (GPR), magnetometry or magnetic susceptibility that measure physical properties of the earth (Gaffney and Gater 2003). Buried cultural materials typically have different physical and/or chemical properties to those of the sediments within which they are buried, and can thus be mapped with geophysical techniques. This practice is termed 'archaeological geophysics' or 'archaeological prospection' (Clark 1996; Gaffney and Gater 2003:12; Johnson 2006). Anthropogenic activities, such as the construction of a mud-brick wall, the transfer of soil from one location to another as might occur during the construction of a ditch, or the mounding of discarded shell material from meals, can lead to localised alterations in the sediments. These differences in physical properties can be measured and mapped vertically and horizontally using geophysical instruments, thus leading archaeologists to a better understanding of cultural features and the spatial relationships between them and the landscapes in which they occur.

In addition, geoarchaeological and mineral magnetic studies of site sediments themselves can be used to assist in the understanding and interpretation of site formation and uses, by examining directly those physical properties created or affected by anthropogenic activities (e.g. Holliday 2004; Rapp and Hill 1998; Waters 1992). When combined with standard excavation they provide a powerful complementary way to understand archaeological site settings.

Traditional uses of archaeological geophysics demonstrated the ability of these tools to locate, map and produce images of buried cultural material (Conyers 2011). Internationally there is now a shift towards using geophysical data as tools for developing and testing innovative hypotheses about human behaviour (Aspinall et al. 2008:245; Conyers and Leckebusch 2010). Innovation within geophysical research, specifically as related to human landscapes, also relies on integration with other techniques utilised in environmental science. As noted by Thompson and Oldfield (1986), mineral magnetic studies have become a standard tool in landscape studies, principally because they can be used to investigate both natural and cultural environments. When combined with complementary methods, such as geoarchaeology and dating, they can be used to understand temporal change, the development of culturally enhanced areas, soil layers or features, and site formation processes in archaeological contexts (Dalan 2001, 2008).

1.1.1 Research Objectives

Applications of geophysics in archaeology have been practiced now for several decades and have become widespread throughout the world; however, in Australia their use has been limited (see ‘Chapter 2’ for discussion as to why this has been the case). Despite this, interest in using these methods is steadily growing with the recognition that they have the potential to provide information about archaeological sites that otherwise may not be obtained using traditional methods alone.

Contemporary archaeological geophysical research in Australian archaeology is, with a few exceptions, still in its early stages, where applications primarily involve geophysical techniques being applied as an initial step towards locating and delineating sites prior to excavation. While studies on how to identify sites, and collect and process geophysical data in different environmental contexts are beneficial, such approaches lack the shifts experienced internationally towards developing new approaches that allow specific research questions to be addressed through (Aspinall et al. 2008; Conyers and Leckebusch 2010). If internationally archaeological geophysics as a discipline is now shifting towards using these methods to directly study the human past, we can start to question how this might be applied in Australian archaeological contexts.

For this doctoral research, the ultimate goal is to incorporate these shifts in archaeological prospection by applying geophysical techniques with a specific goal of addressing important questions in Australian archaeology, with a particular emphasis on sites in the north of the continent. The primary target of this research is on magnetic susceptibility, the second research focus is on GPR.

Firstly, the examination, potential use and comparability of geophysics, in particular sediment magnetic susceptibility, with other techniques like geoarchaeology, soil chemistry and geochronology will be used to understand the record of occupation, stratigraphy and site formation processes in northern Australian archaeological sites. Specifically, these techniques will be used to understand human colonisation patterns in Australia and to determine if sediment magnetic susceptibility can be used as a diagnostic tool in Australian research (see Chapter 3 – techniques paper).

Secondly, the examination and potential use of GPR, with archaeological excavations, geographic information systems (GIS) and statistical analysis will be used to understand site formation processes and burial practices in northern Australia sandstone rockshelter.

Initial colonisation of anatomically modern peoples arrival into Australia is a much-debated subject and identifying modern human behaviour and its appearance in the archaeological record are critical for establishing colonisation events (i.e. Out of Africa) (Franklin and Habgood 2007; O'Connell and Allen 1998). For nearly half a century there has been ongoing debate in Australian archaeology regarding the timing (i.e. when) and nature (i.e. from where and how) of initial colonisation, with multiple different settlement models proposed (cf. Birdsell 1977; Bowdler 1977; Bowler et al. 2003; Hiscock 2008:45; Smith 1989, 1993; Veth 1989).

In the absence of any built structures and minimal known stratified open sites in the ancient Australian landscape, rockshelters are the major source of detailed information for understanding the timing and nature of late Quaternary human occupation of the continent (e.g. Allen and O’Connell 1998; O'Connor et al. 1999; Smith and Sharp 1993; Ward et al. 2006; Watchman et al. 2001). The outcomes from many rockshelter studies have been limited, due to issues of stratigraphic complexity and the methods involved for recognising episodes of human occupation (Farrand 2001; Stein and Farrand 2001). Isolating individual occupation surfaces is difficult because of reoccurring human habitation (Straus 1990:266), while others note methodological (i.e. reliable dating material) and technical problems in sedimentary analyses (O'Connor et al. 1999; Straus 1990). Reoccupation of a site may also result in vertical displacement of artefacts, a consequence of human trampling and/or treadage (cf. David et al. 2007; Gifford-Gonzalez et al. 1985; Hughes and Lampert 1977; Nielsen 199; Richarson 1992, 2010; Stockton 1973). Conventional archaeological techniques have yielded considerable information on the timing and nature of Australian rockshelter occupation but association of sediment ages with clear evidence of human occupation is generally lacking.

Two key sites with relevance to debates about colonisation models are Gledswood Shelter 1 (GS1) and Madjedbebe (formally Malakunanja II); both are Pleistocene-aged sandstone rockshelters located in northern Australia. Madjedbebe, located near the coast, is arguably Australia's oldest known archaeological site, having been settled by at least 50 ka (Roberts et al. 1990b) while GS1, located in the interior savannah, was settled by at least ~ 38,000 ka (Wallis et al. unpub data) (Figure 1.1).

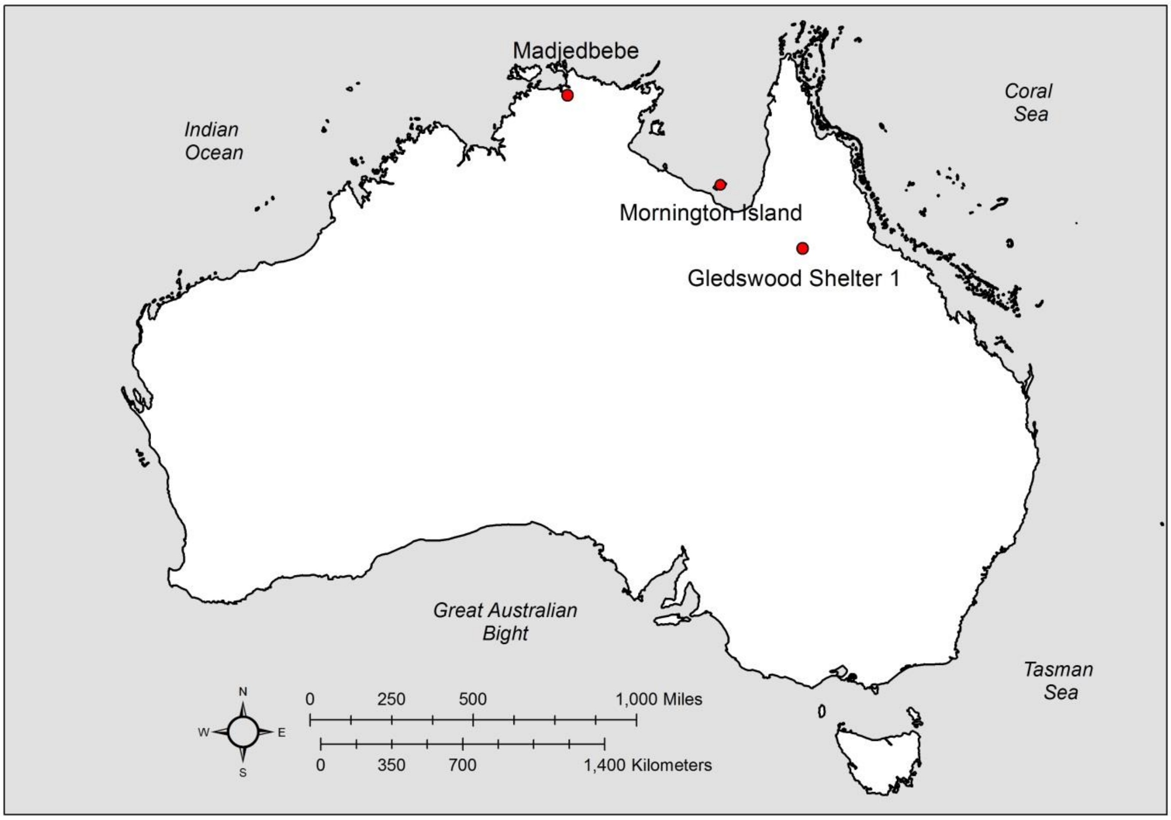

Figure 1.1 **Map showing the location of study areas: Madjedbebe (formally Malakunanja II), Gledswood Shelter 1 and Mornington Island, northern Australia.**

A much-debated subject concerns when humans first colonised the continent. Most archaeologists accept that Australia was occupied anywhere from 45,000 to 50,000 years ago, while claims of an older occupation are generally dismissed by mainstream archaeologists (Hiscock 2008:27–28). One of Australia's oldest rockshelter sites, Madjedbebe, has been at the centre of this debate because sediments several meters below the surface in which artefacts were found yielded luminescence dates of between 50,000 to 60,000 years (Roberts et al. 1990a). However, several archaeologists are doubtful of the dates and question the stratigraphic associations at the site (Allen 1994; Allen and O'Connell 2003; Bowdler 1990; 1991; Hiscock 1990; O'Connell and Allen 1998; O'Connell and Allen 2004). They have argued that at least some of the artefacts, especially those found in the deepest layers, are not in fact *in situ* and are instead the result of vertical movement downwards through the deposit and consequently, the dates estimated for the site are inaccurate.

Another issue among Australian archaeologists has been about understanding 1) the timing and persistence of human occupation and 2) the nature of climate change and its effects on people in the interior of northern Australia (cf. Bowler et al. 2003; Hiscock 2008:45; Horton 1981; Smith 1993; Veth 1989). Presently there are limited sites in central Australia that provide insight into the timing and nature of human occupation. Gledswood Shelter 1 (GS1) is one such site, situated in a region that has been characterised as a potential corridor for early colonists moving into the arid interior. Stone artefacts recovered at the site have been dated to ca 38,000 years (Wallis et al. unpub data). However, questions regarding whether the deepest artefacts at GS1 are *in situ* or if occupation of this site was continuous, intermittent or abandoned through the height of the last glacial maximum (LGM) – a period of significant environmental change – have not yet been satisfactorily answered (see O'Connor et al. 1999).

A key component towards understanding and resolving these issues is an understanding of the site formation processes within the archaeological site. Issues of stratigraphy, particularly recognising and dating discrete episodes of human occupation, have been the major reason for why such debates continue to persist. An understanding of site formation processes can provide an understanding of the depositional history and the people associated with it. To address these key issues, geophysical applications particularly magnetic susceptibility, were used at three northern Australian sites to understand the episodes of human occupation and behavior, and the site formation processes. These three sites have been established as case studies for addressing four research questions framed within issues in Australian archaeology:

1) Can magnetic susceptibility be used to understand archaeological site formation processes, including determining the onset of human occupation, and resolving issues regarding artefact movement and apparently 'instantaneous' deposition of materials?

2) Can magnetic susceptibility be used to understand the nature and persistence of human occupation at a Pleistocene-aged rockshelter in interior northern Australia, with particular emphasis on the relationship with changing climatic regimes such as the LGM?

3) Can GPR be used to identify human burials in a geologically complex rockshelter deposit, and if so, can it also be used to support pre-existing traditional knowledge of burial practices?

4) Can magnetic susceptibility when integrated with geoarchaeology, be used to understand whether open sites (shell mounds) on Mornington Island, Gulf of Carpentaria, were repeatedly visited?

Magnetic susceptibility is a measure of the ease with which a material can be magnetised in the presence of a magnetic field (Dalan and Banerjee 1998; Thompson and Oldfield 1986:25). The susceptibility of a sediment to magnetisation is dependent on the composition, concentration and grain size of the magnetic minerals from which it is comprised. Mechanisms causing magnetic enhancement and thus increases in magnetic susceptibility include anthropogenic activity such as burning (cf. Jordanova et al. 2001; Oldfield and Crowther 2007) or processes such as pedogenesis (cf. Dalan and Banerjee 1998; Dearing et al. 1996); weathering (dissolution or cation substitution of magnetic minerals, cf. Evans and Heller 2003) or formation of bacterial magnetosomes (cf. Linford 2005).

Magnetic susceptibility studies are a successful proxy for understanding site formation processes because they can reveal variations in sediment input that may result from these mechanisms and/or processes (cf. Dalan 2008; Dalan and Banerjee 1998; Ellwood et al. 1995; Jordanova et al. 2001; Linford et al. 2005; Maher 2011; Maki et al. 2006). Globally, these techniques have been shown to be an important tool for understanding past human occupation as well as environmental changes in Pleistocene rockshelter and cave deposits though they have been applied to a few restricted areas such as parts of Europe and Africa (Ellwood et al. 1997, 2004; Herries 2006; Latham and Herries 2004). As magnetic susceptibility has the potential to provide information about rockshelter stratigraphy that otherwise may not be obtained using traditional methods, and with only a few applications utilised in Australian rockshelters (see, however, Keys 2009 and Marwick 2005) it was chosen specifically for this research.

Some of the research in this thesis aims to investigate the magnetic susceptibility of sediments from a sandstone rockshelter in northwest Queensland to understand human occupation during the height of the LGM, and whether this method can assist with understanding the onset of human occupation. Magnetic susceptibility was also used to investigate the sediments in three shell mounds on Mornington Island, in the Gulf of Carpentaria to understand the nature and persistence of human occupation of open sites. Both site regions are comprised primarily of weakly magnetic quartz sand. As such, magnetic enhancement should result from burning (human induced or natural) or pedogenesis. For these sites, I determine whether there are correlations between enhanced (or reduced) magnetic signatures and artefact densities within the sedimentary sequence. Correlations between the two would demonstrate that magnetically enhanced (or reduced) sediment inputs are largely a result of anthropogenic activity and not natural processes.

I also examine whether there are any correlations between enhanced magnetic signatures and cultural materials, geoarchaeology, soil chemistry and geochronology at GS1 and the three shell mounds. These analyses will aid in determining cultural (i.e. fire) from natural (i.e. pedogenesis, roof fall, chemical weathering) inputs during the period of site formation and use, and will help resolve issues about deposit complexity and the potential for sediment mixing and artefact movement (David et al. 2007; Murphy and Mandel 2012). In combination, the results provide detailed information on site formation processes and a reconstruction of the palaeoclimatic history of northern Australia, a region for which very few terrestrial palaeoenvironmental records exist.

Since the outcomes from many rockshelter studies have been unsatisfactory due to evidence for human occupation, the use of mineral magnetic techniques, which can distinguish cultural from natural deposits, are critical in understanding complex stratigraphies. Sediment magnetic susceptibility studies have a significant potential to be used as a diagnostic tool for assessing the integrity of archaeological sequences in Australian rockshelters. This study is the first in Australian archaeology to use detailed mineral magnetics techniques to understand site formation processes. Significantly, this research not only improves our understanding of how human activities influence the accumulation of sedimentary deposits in sandstone rockshelters and shell mounds, but also allows the reconstruction of the palaeoclimatic history of northern Australia, which by and large is a major contribution in both Australian prehistory and palaeoenvironmental studies.

GPR, another geophysical instrument used for this research, has a variable record in identifying human burials, being least effective when distinctive burial features such as grave shafts or void spaces are not present such as shell middens. GPR works by transmitting electromagnetic energy in the form of radar waves into the ground (Bevan 1998; Conyers 2012). When the wave encounters a contrasting material in the soil (such as air voids, stone or moisture content), a reflection occurs, sending part of the wave back to the surface, where it is received and recorded. The remainder of the wave continues downward until it too is reflected back to the surface by deeper objects, or dissipated through absorption by subsurface materials. The depth of radar wave penetration and velocity is highly dependent on soil type and moisture conditions, or the dielectric properties (the ability of a radar wave to hold and transmit an electric charge).

Additionally, I use GPR to understand the site formation processes related to Indigenous burials in a shell midden deposit located within a sandstone rockshelter in northern Australia. This GPR study was carried out in advance of archaeological excavations at Madjedbebe. The results were tested and compared to the test excavation and detailed GIS mapping data to understand the nature of the deposits, specifically the formation processes related to complex human burials. Application of this methodology documented a marker for burial identification in this region and provided a useful management tool for Indigenous communities and other heritage practitioners.

1.2 Archaeological Background

About 50,000 years ago (Hiscock 2008:34–35; Mulvaney and Kamminga 1999: 138-146), humans are inferred to have journeyed through Sunda into what is known as Sahul (aka ‘Greater Australia’, this being the combined landmass of Australia, Tasmania and Papua New Guinea) (Figure 1.2). Lower sea levels than present-day, combined with technological, cultural and social innovations by these early peoples, allowed them to travel into an area that had never previously been inhabited by hominids. Archaeological research has been critical in understanding the movement and adaptations of these early peoples. Yet knowledge of this long-term cultural history and the nature of *initial colonisation* of the continent remains of research significance in and outside of Australia today (Davidson and Noble 1992; Franklin and Habgood 2007). Such issues include who were the first Australians, the origin of colonisation, and the patterning and timing of human settlement in the different biogeographic zones (cf. Birdsell 1977; Bowdler 1977; Bowler et al. 2003; Hiscock 2008:45; Smith 1989, 1993; Veth 1989).

Understanding modern human behaviors, such as these would have been critical for the successful inhabitation of the challenging Australian landscapes, which underpins much broader understandings of earlier movements of hominids out of Africa and across the globe (Franklin and Habgood 2007). Initially Bowdler (1977) argued that the colonisation of Australia was largely achieved by an initial focus on coastal environments (since early people would have possessed maritime skills and economies as evidenced by their maritime navigation to northern Australia). However, others like Veth (1989), Smith (1993) and Bowler (2003) have shown that these early peoples adapted rapidly to the extreme arid conditions of the interior, thus indicating that social and economic skills were not just limited to coastlines.

Factors influencing explanations for human movement into the interior fall into two camps: (1) biogeographical, whereby the landscape is seen as a series of refuges, barriers and corridors that offer different resources, opportunities and challenges to people (cf. Veth 1989; see also Horton 1981); and (2) environmental, whereby higher rainfall and more surface water prior to 30,000 years ago may have meant the challenges presented by arid Australia to early colonists were somewhat lessened (cf. Hiscock and Wallis 2005). The biogeographical model of Veth (1989, 1993) proposed that early humans occupied much of the inland rapidly and easily, but that they avoided the water-scarce sand ridge deserts designated as barriers. Piedmont uplands and riverine/gorge systems that were less sensitive to changing climates and easier to inhabit owing to great water availability were refuges, while corridors incorporate all other areas and may have been either passage ways for settlement or barriers, depending on past climatic conditions (Veth 1989:49). The latter suggests that much of the interior was occupied but during a time when surface water, rainfall and food resources were more abundant. Hiscock and Wallis (2005) argued that initial colonists in Australia's interior were not fully adapted to inland arid environments similar to those experienced today; instead, they argue that people moved into those areas when surface water was more plentiful and climatic conditions were more favorable, and therefore gradually adapted *in situ* to the aridity of the LGM.

Associated with these pathways of initial settlement is a related debate on the nature and persistence of occupation of interior sites between 23,000 and 19,000 years BP, the peak of the LGM, when temperatures were on average 9°C cooler in the southern half of Australia (Magee et al. 1995; Magee and Miller 1998; Miller et al. 1997; Petherick et al. 2011; Williams et al. 2009). Veth (1989:81) suggested that continuous occupation of some arid habitats occur during the terminal Pleistocene (cf. Smith 1989; 1993) and that abandonment of others occurs at the height of the LGM. While some sites such as Lawn Hill, Fern Cave, Milly's Cave and Puritjarra demonstrated persistent and intensified occupation during the LGM (Hiscock 1988; Lamb 1996; Marwick 2003; Smith 1989, 2009), others have no evidence of cultural material during that time, suggesting abandonment of the local environment (Hiscock 2008; O'Connor, et al. 1999; Veth 1989) (see Figure 1.2). Veth (1989:81) argued the observed archaeological patterns fit a biographical model of continuous occupation of some well-watered 'refuges' within arid habitats during the terminal Pleistocene with widespread episodic or repeated use of the remainder of the arid interior through the LGM (cf. Hiscock and Wallis 2005).

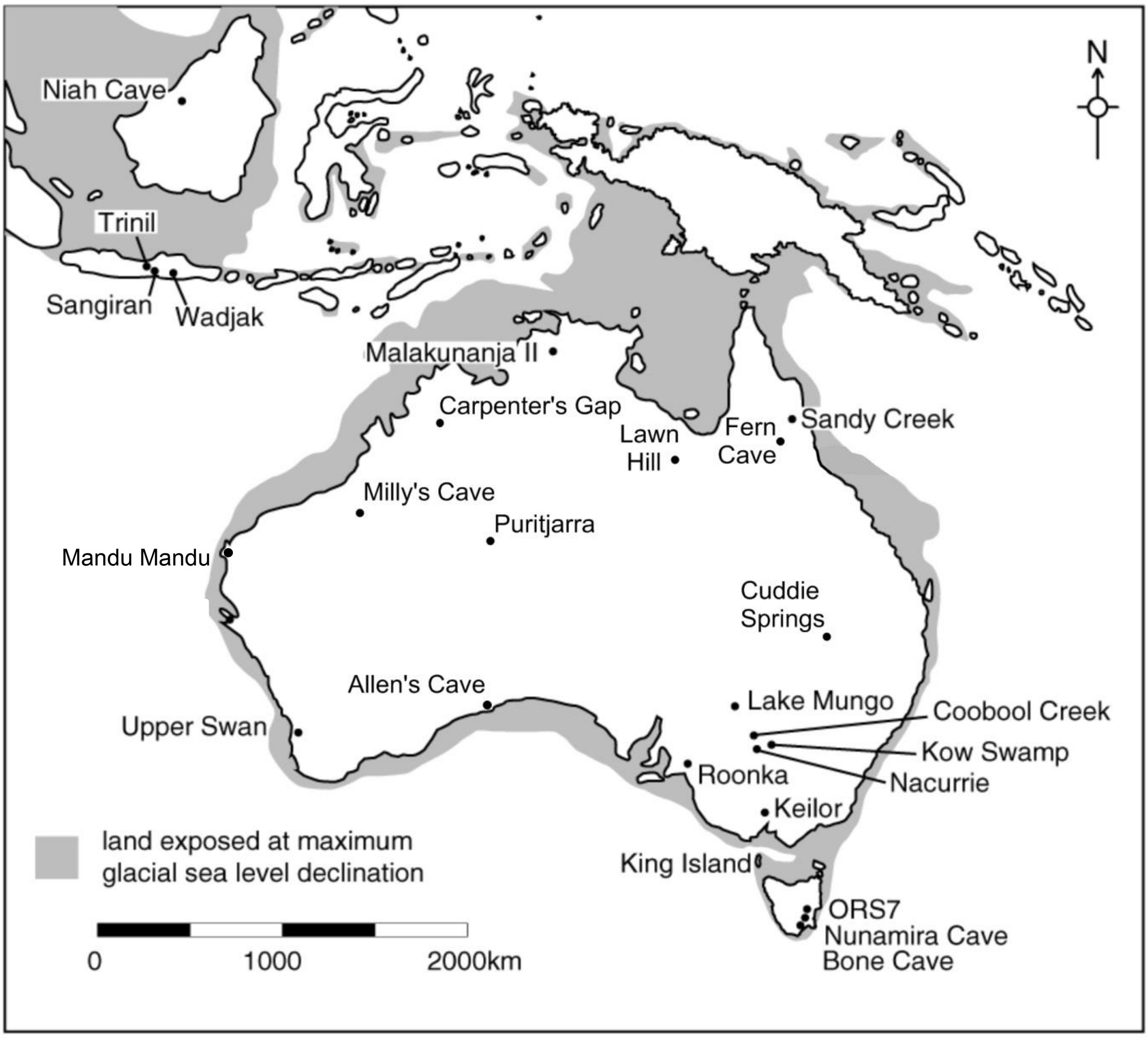

Figure 1.2 Map of Australia showing Pleistocene sites and Sahul landmass (grey) during the LGM (modified from Brown 1997).

The timing of arrival and movement of anatomically modern peoples into Australia is a fundamental issue in archaeology. With no real development towards resolving these issues, new approaches are necessary in archaeological research. Gledswood Shelter 1 represents an important site that falls within these early colonisation models. Located in northern Australia and dating to the Pleistocene, the site makes is an extremely significant to the study of Australian cultural history.

1.3 Study Region

All study sites are located in northern Australia, and both rockshelter sites are located in sandstone escarpment areas (see Figure 1.1). The GS1 site is located in north Queensland, geographical coordinates 19.32°S, 143.14°E (Figure 1.3). This site is roughly 120 km (74 mi) north of Richmond, about 380 km (236 mi) east from Mount Isa and 420 km (260 mi) west of Townsville. Madjedbebe is located in the Northern Territory in an excised part of Kakadu National Park, geographical coordinates 12.48°S Latitude, 132.90°E (Figure 1.4). This site is roughly 22 km (13 mi) northeast of the small township of Jabiru, which is about 220 km (136 mi) southeast of Darwin. The third study area, Mornington Island, is located in the Gulf of Carpentaria, between latitudes 10° and 17.30°S and 135.30 and 142°E (Rosendahl 2012) (Figure 1.5). This area, designated as the Wellesley Islands, contains a number of offshore islands and archipelagos.

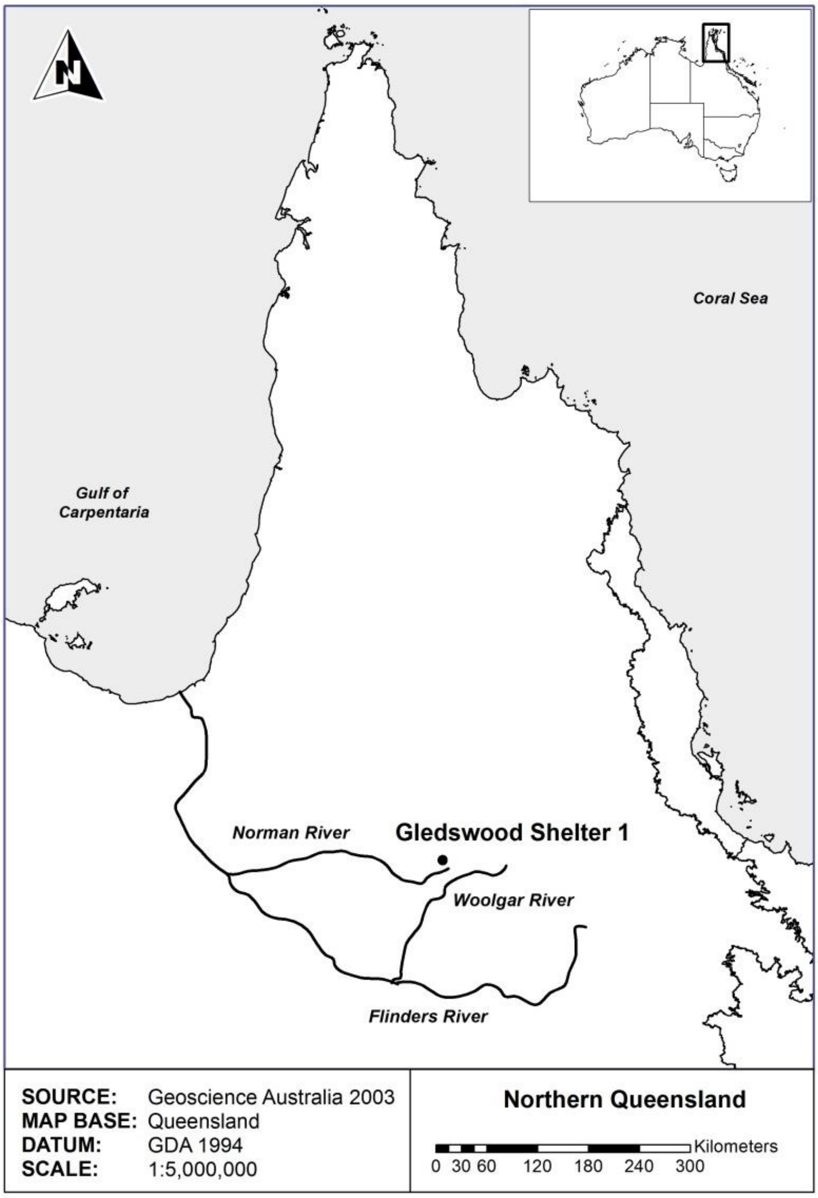

Figure 1.3 **Map showing the location of GS1 in north Queensland, Australia.**

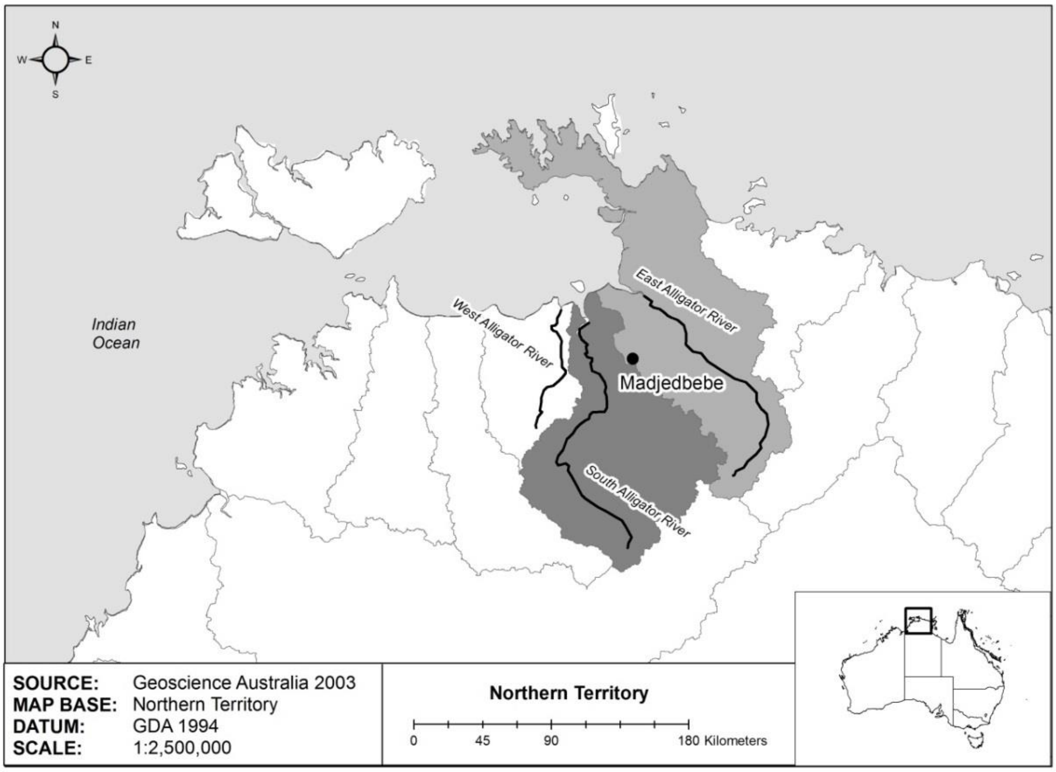

Figure 1.4 Map showing the location of Madjedbebe (formerly Malakunanja II) in north Australia. Major river catchments highlighted in grey.

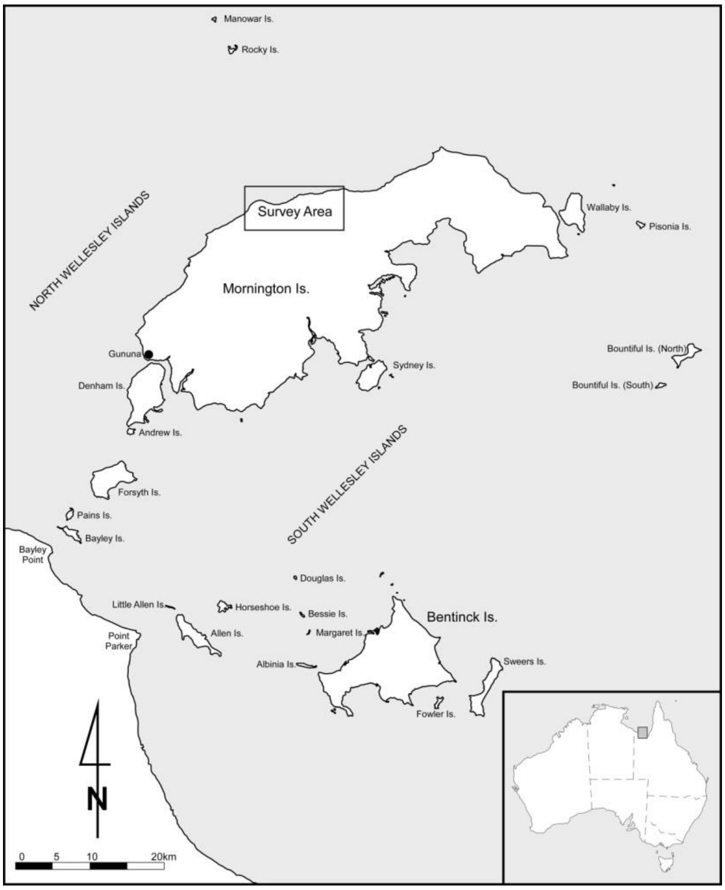

Figure 1.5 Map of the Wellesley Island group and location of study area (small box) in the Gulf of Carpentaria (Rosendahl 2012:Figure 2.2).

1.3.1 Inland Queensland

The GS1 site is located on a sandstone escarpment in the western foothills of the Gregory Ranges, a few kilometres north of the Norman River in north Queensland (Figure 1.6). The site is situated on Middle Park Station, a pastoral property owned by the Woolgar Valley Aboriginal Corporation (WVAC) (Indigenous Land Council [ILC] 2008).

The site area falls within the semi-arid tropical region with a surrounding vegetation primarily of open woodland and grasslands. Rainfall is limited with most occurring during the wet season from November to March. Mean annual rainfall is low, ranging between 600 and 800 mm, and temperatures remain high all year round, about 30–33°C (Figures 1.7 and 1.8; Bureau of Meteorology 2013). It is the seasonal rainfall that supports all ephemeral river systems, with high river flows during the wet season and low to almost no flow in the dry season. Major rivers near GS1 include the Norman River located 1.5 km south and the Woolgar River located 25 km southeast, both of which are part of the Southern Gulf Catchment System (see Figure 1.3). The headwaters for both are located in the Gregory Ranges and both drain into the Gulf of Carpentaria, the Norman River directly and the Woolgar River via the larger Flinders River.

Figure 1.6 Aerial photograph of GS1 showing the surrounding open woodland vegetation and sandstone outcrop against which the rockshelter has formed (courtesy of Lynley Wallis).

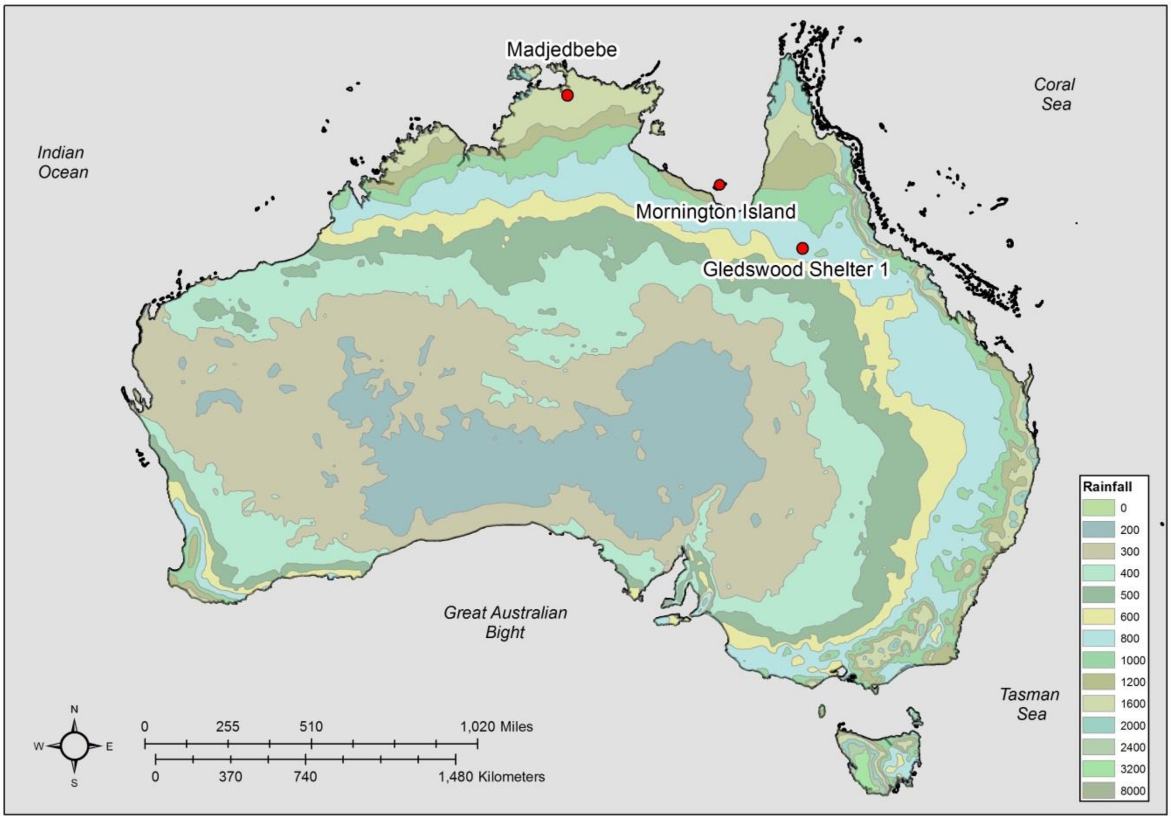

Figure 1.7 Image showing the average annual rainfall (mm) for Australia.

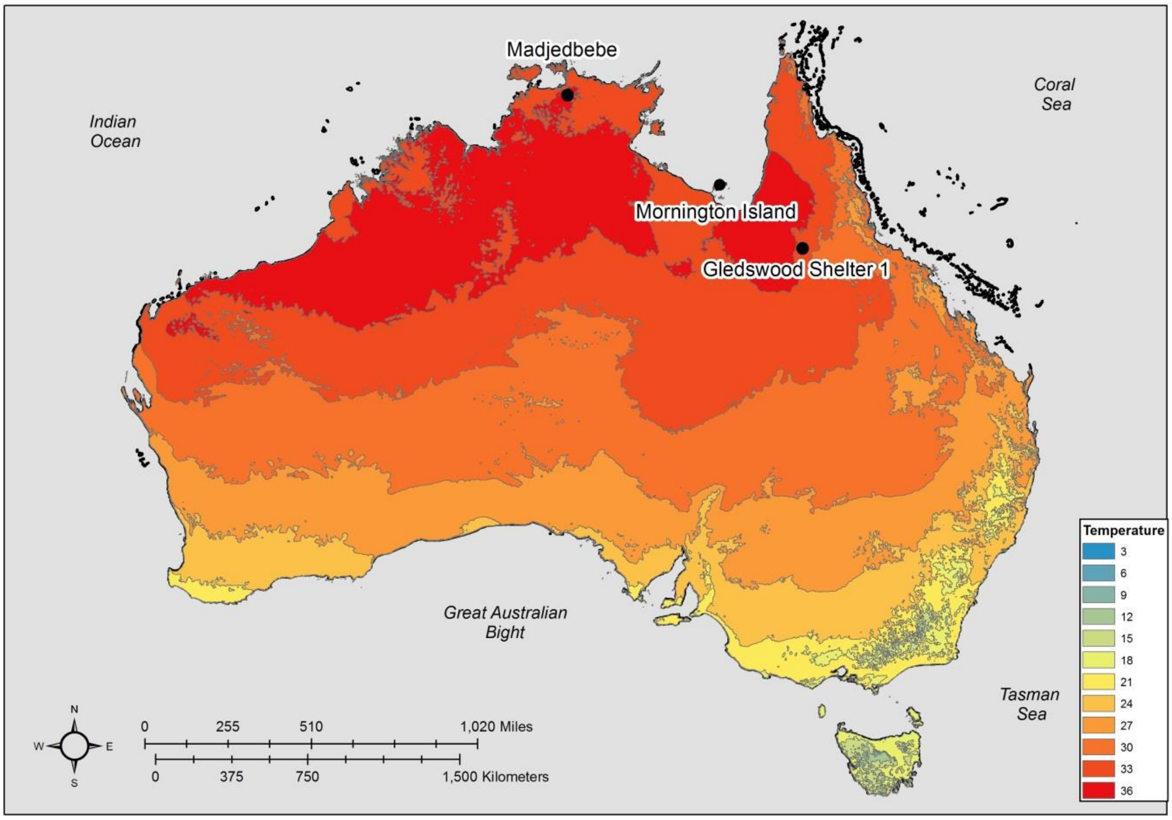

Figure 1.8 Image showing the average annual maximum temperature (°C) for Australia.

Gledswood is situated at the base of a weathered 8 m high Mesozoic sandstone outcrop overlooking a lightly wooded sand sheet (see Figure 1.6). This sand sheet extends south and west from the outcrop for 60 m before dropping off into a seasonal drainage area. The shelter itself, which is located adjacent to the outcrops' southern face, is about 7 m wide with an average height of 3–5 m at the drip-line, and a maximum depth of 3 m from the back wall to drip-line (Figure 1.9 and 1.10). Today, the shelter floor is about 20 m² and supports minimal vegetation. Most of the floor is comprised of sands and silts and appears well protected from the effects of precipitation, as no significant erosion or sheet wash is apparent (Keys 2009:10). The landscape surrounding the shelter consists of a number of sandstone boulders and exposed bedrock outcrop.

Characteristic of many overhangs in this region, GS1 also contains stenciled art and pecked geometric motifs (Wade et al. 2011; Wallis et al. 2009:71) (Figure 1.11). The site was first visited in 2005, at which time charcoal, a portable grinding slab and flaked stone artefacts were noted on the site's surface. The following year three 1 m^2 adjoining test-pits (Squares D1, D0 and C0) were excavated at the site, at the end of which stone artefacts were still being recovered from 180 cm below surface in Square C0 (see Figure 1.10). A second field season in 2008 saw an additional three squares (Squares C1, B1 and B0) excavated (see Figure 1.10). Radiocarbon dating from the first season revealed that GS1 contained a pre-LGM and late Pleistocene/Holocene sequence dating to about 38,000 yrs BP (Wallis et al. 2009:72). This indicatied that Gledswood was a focus for human occupation through the late Pleistocene and Holocene, with major shifts in land-use strategies during the mid-Holocene (cf. Morwood 1992).

Figure 1.9 Photograph looking north, showing GS1 site and surrounding vegetation (Lynley Wallis and Kelsey Lowe to right and left of view, respectively).

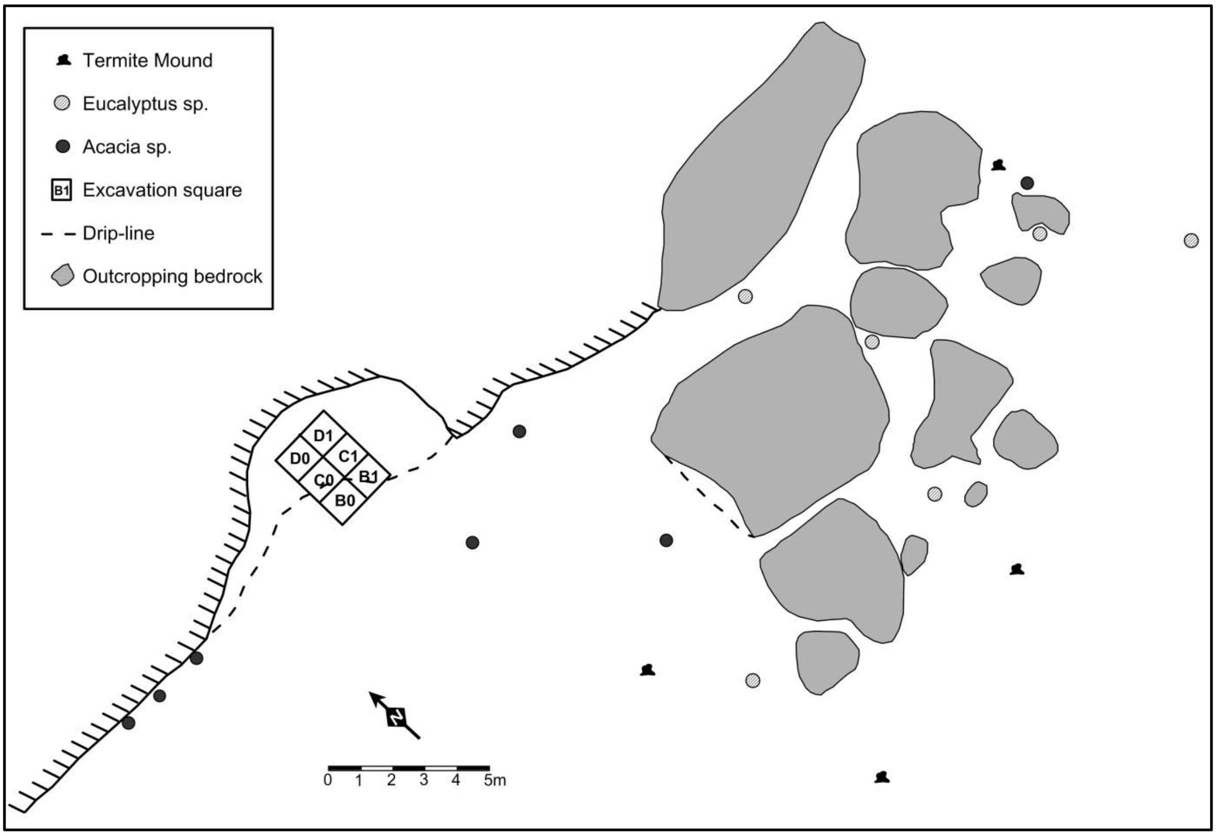

Figure 1.10 Site plan of GS1 showing excavation square locations (Wallis et al. 2009:Figure 1).

Figure 1.11 Left hand stencil with red pigment on GS1's shelter wall (unscaled).

The GS1 site falls on the boundaries boundary between two bioregions: the Torwood Land System to the east, which is characterised by residual slopes, scarp retreats and plateaus of the Gregory Ranges; and the Strathpark Plains to the west, which consists of gently sloping plains that flank the Norman River (Perry and Lazarides 1964) (Figure 1.12). The Hampstead sandstone outcrops, which are situated atop eroded Precambrian sedimentary rock surfaces, are the dominant material in the Torwood Land System (Smart 1973:12). Both the Strathpark Plains and Gregory Ranges contain Mesozoic-aged sandstones, but elevation differences resulting from major tectonic events have created two different environments; GS1 is situated on an outcrop in the transition zone between the two.

The landscape surrounding GS1 has been affected by several phases of Quaternary weathering and erosion. Today much of the area is dominated by sand and silt outwashes, which eroded from sandstone rocks and outcroppings. While many of these environmental changes are a result of precipitation and climate, the quartzose rich deposits in the Strathpark Plains are argued to have developed by *in situ* weathering (Smart 1973).

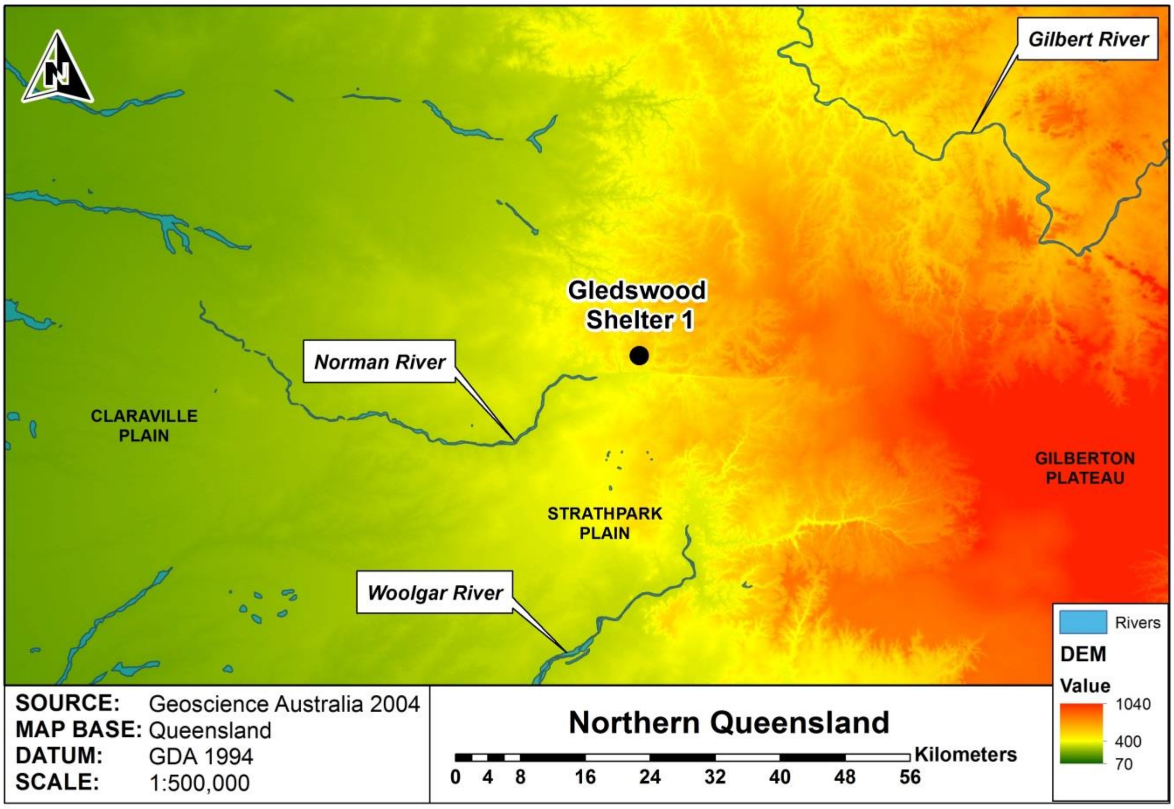

Figure 1.12 **Topographical setting of GS1 and surrounding area using digital elevation model (DEM) data.**

1.3.2 Northern Territory

Madjedbebe is located in the Alligator Rivers region of Kakadu (in an area excised from the surrounding Kakadu National Park), an area that extends southwards from the coast of Van Diemen Gulf to the Arnhem Land plateau in the Northern Territory (see Figure 1.4). Geologically, this area is comprised of dissected sandstone plateaus and escarpments, lowland plains, floodplains (both estuarine and basin) and narrow coastal plains. Like GS1, Madjedbebe is located on a sandstone escarpment, a cross-bedded quartzose sandstone which is part of the Kombolgie Formation of the Middle Proterozoic age (East 1996:40). To the east, the site is bounded by the Arnhem Land plateau, while to the west the Magella floodplain is the predominant landscape feature.

The site is situated in the East Alligator, West Alligator and South Alligator catchment, these all being rivers that drain north into Van Diemen Gulf (see Figure 1.4). Madjedbebe is located about 9 km west of East Alligator River and 50 km east of South Alligator River. The climate in this region has been classified as ‘summer rainfall-tropical’ with two broad seasons: one warm and dry, the other humid, hot and wet, with an annual maximum temperature between 33–36°C. The former is characterised by dry and mild-warm conditions from April to October, the latter by heavy periodic rainfall and hot-humid conditions from November to March (McQuade et al. 1996) (see Figure 1.8). Average annual rainfall is from 1200–1600 mm (Bureau of Meterology 2013) (see Figure 1.7). Climate and the hydrology constitute major mechanisms for both landscape and environmental changes in this area, specifically during the Quaternary with changing sea levels (Nanson et al. 1993).

Madjedbebe is a narrow, northwest facing shelter situated on a low-gradient sand sheet that developed at the foot of the sandstone escarpment (Kamminga and Allen 1973:45; Roberts et al. 1990b). This sand sheet extends outwards (>100 m) from the site, towards the lagoon, where it eventually terminates. The shelter is long with a minimal overhang and an ashy deposit that extends about 10 m from the back wall (Figure 1.13). The site boundaries (based on the presence or absence of cultural material) have not been fully determined and rock art visible along at least >50 m length of the shelter wall suggests it may have been extensive. The gallery of rock art, like many sites elsewhere in Arnhem Land contain colourful pictures depicting guns, ships, weapons and Europeans (May et al. 2010; Wesley 2013; Wesley et al. 2012), as well as beeswax art (Welch 1995) and several x-ray images of barramundi and long neck turtles (Chaloupka 1985; Lewis 1988) (Figure 1.14).

Rock art paintings such as these are thought to depict Aboriginal responses to social and political changes as well as the environmental transformations in this region (Lewis 1988). X-ray paintings, which show skeletons and/or internal organs are thought to be less than 4,000 years old (Taçon 1993) and often reflect environmental variations of the late Holocene landscape. Fish and turtles, as seen at Madjedbebe, were depicted more in areas near the coast while kangaroos were depicted inland. Paintings of ship vessels and figures with ‘hands on hips’ motifs often represent contact, first with the Macassans, foreign fisherman who arrived in 1720 to fish for trepan (Mitchell 1994). Later depictions represent Europeans who introduced objects such as guns and iron, and stood in a particular way that was much different than the Aboriginal stance (i.e. hands on hips) (May et al. 2010; Wesley et al. 2012; Wesley 2013).

Figure 1.13 Madjedbebe looking east towards the shelter and floor, note limited overhang. Rock art is present along the extent of the shelter wall and continues along the wall behind the tree. A geophysical grid and the Bartington-601 gradiometer are adjacent to shelter wall.

Figure 1.14 Unscaled rock art at Madjedbebe, depicting a European figure with hands-on-hip style (left arrow) and an x-ray design barramundi (centre).

Madjedbebe was originally excavated by Jo Kamminga and Harry Allen in 1972 (Kamminga and Allen 1973) as part of an environmental study for the proposed Kakadu National Park. They excavated a 1 x 0.80 m pit located near the back wall to a depth of 2.48 m, encountering a 60-cm thick shell midden near the surfaces as well as an abundant mix of faunal bone and stone artefacts (Figure 1.15). The site was re-excavated by Rhys Jones, Bert Roberts and Mike Smith in 1989 (Roberts et al. 1990b). Their 1 x 1.5 m pit was placed 0.5 m in front of Kamminga and Allen's pit and was excavated to a depth of 2.87 m (see Figure 1.15). Nine thermoluminescence (TL) dates and two radiocarbon dates confirmed that people arrived at the site between 61,000–45,0000 years ago, making it one of Australia's oldest sites and potentially marking the time of initial colonisation on the continent (Roberts et al. 1990b:155). In addition to the dates, more than 1,500 artefacts were recovered from the site. The site was again re-excavated in 2012 by the University of Queensland under the direction of Chris Clarkson, Richard Fullagar, Tiina Manne, Ben Marwick, Mike Smith and Lynley Wallis after a geophysical survey using GPR was completed in 2011. Approximately, nine 1 x 1 m square pits and two smaller pits located adjacent to the 1972 and 1989 pits were excavated to a maximum depth of 3.6 m (see Figure 1.13 and 1.15).

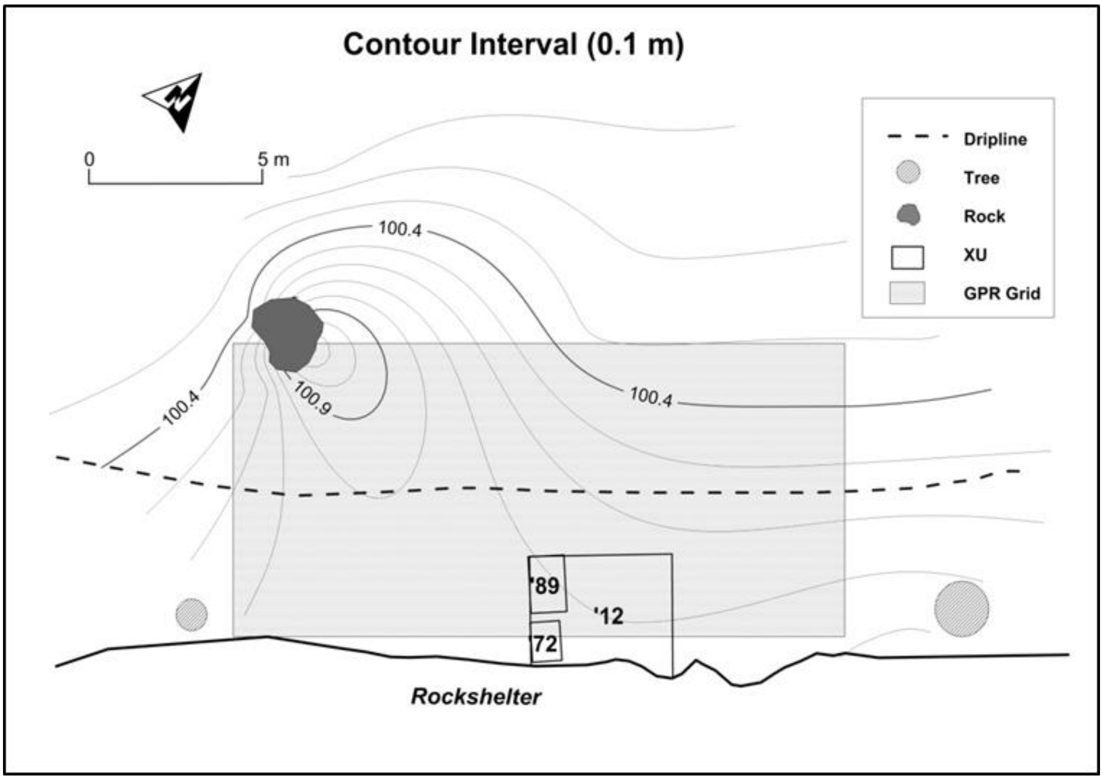

Figure 1.15 **Topographic map of Madjedbebe, with previous excavation units (XU), GPR grid and the 2012 investigations.**

The physical landscape of the site and surrounding region dates back to the early Proterozoic times, almost 2000 million years (Ma) (East 1996). Geologists have defined this region as the Pink Creek Geosyncline (Needham and Stuart-Smith 1984), an unevenly deformed and mineralised mix of meta-sedimentary and igneous rocks and young sandstones of the Kombolgie Formation, which overlie the Archean basement rocks of the Nanambu Complex (~ 2500 Ma) (Hein 2002; Needham 1988) (Figure 1.16). The Kombolgie Formation consists of medium to coarse-grained quartz sands, basal quartz and conglomerates that were deposited during the onset of the Middle Proterozoic (~1650 Ma), after the upheaval and folding processes of the escarpments and plateaus (Needham 1988). Overall height of the plateaus and escarpments are about 300 m, with some hills rising to 570 m. This region was highly subjected to intense weathering in early to mid-Tertiary times and during extreme climatic and sea level changes of the Quaternary (Nanson et al. 1993), which characterise the weathered landscape of today (Figure 1.17). The Pine Creek Geosyncline is also an area of high mineral prospection and contains several large uranium mines, the closet being 2.25 km to Madjedbebe.

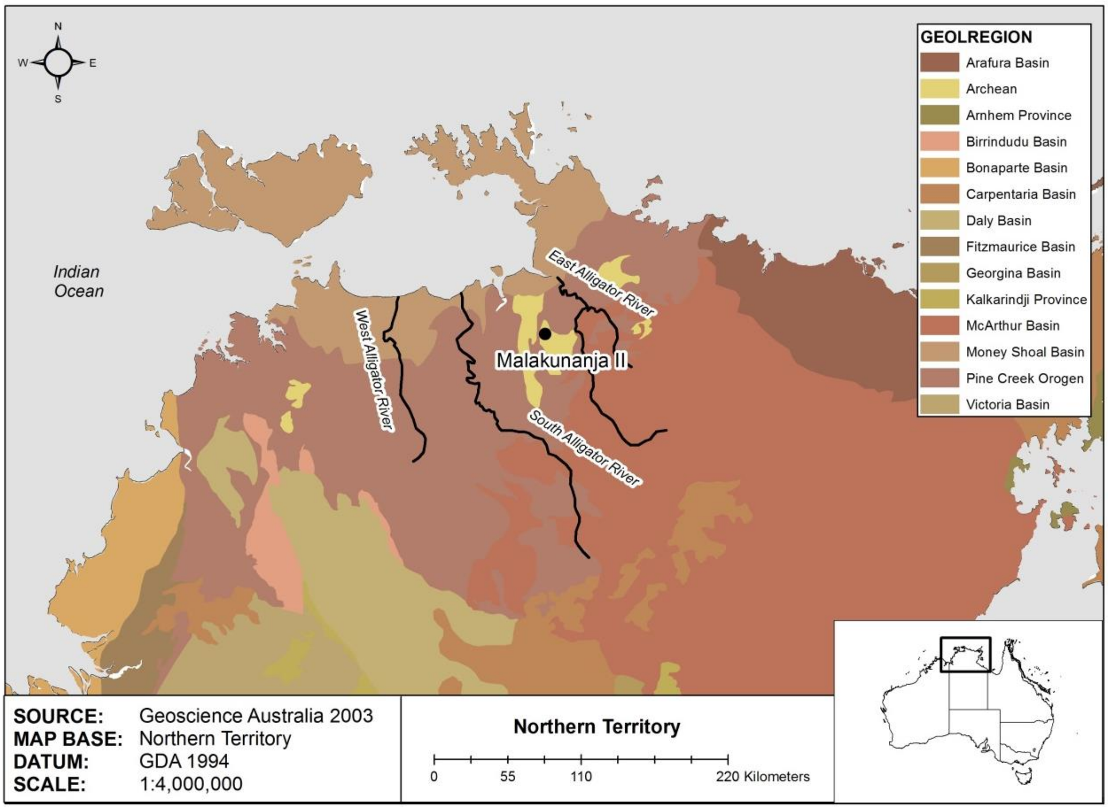

Figure 1.16 **Geological regions surrounding Madjedbebe (Malakunanja II).**

Figure 1.17 Typical geology in the Kakadu Region, sandstone escarpment (courtesy of Tiina Manne).

1.3.3 Gulf of Carpentaria

The Gulf of Carpentaria is an epicontinental sea situated between Australia and Papua New Guinea. It is surrounded by Cape York Peninsula to the east, Arnhem Land to the West and Papua New Guinea in the north. The Carpentaria Plains borders the south. A number of offshore islands and archipelagos are located in the Gulf of which the Wellesley Islands are but one (see Figure 1.5). Comprising more than 23 islands, the Wellesleys are dominated by Mornington Island, the largest island in the Wellesley group covering 966.5 km^2, with a maximum height of 40 m above sea level. While there are a few low sea-cliffs, where the lateritic plateau meets the coastline, the majority of the coastline is low-lying and characterised by depositional environments such as beaches, widespread supra-tidal mudflats, beach ridges, cheniers and aeolian dunes. The main river channels tend to approach the coast directly and are circumscribed by supra-tidal hypersaline mudflats or saltpan. The Sandalwood River catchment or Yiinkan Embayment, the location of the three mounds, Guttapercha, Mala Katha and Munburlda in this thesis, is the largest drainage system on the northern coastline (Rosendahl 2012).

The Wellesley archipelago was formed during the Holocene marine transgression and is part of the Normanton lateritic formation or Normanton Plateau (Grimes 1979). The lateritic bedrock unit, designated as the Mornington bedrock is overlain by mostly sandy red/yellow light textured earths and clay (Grimes and Sweet 1979). A number of swamps and swales located on the northern side of the embayment support soils rich in clay and loam. Characterised by supra-tidal hyper-saline mudflats (saltpan) and mangrove-fringed tributaries and estuaries (including the Sandalwood River), this land adjoins a rich marine environment (Rosendahl 2012). These sandy residuals mark the surface of the mudflats and form on laterite or beach rock platforms. Generally, these act as sediment traps for catching sands and silt during seasonal strong south-easterly winds. The terrain is generally flat and sparsely vegetated.

The Mornington Island region is classified as part of tropical north Australia (Stern et al. 2004), with a relatively short wet season typically from November to March (associated with the Australian Monsoon), and a long dry season from April to October (associated with the Southeast Trade Winds) (Bureau of Meterology 2013). Mean annual rainfall is very low, ranging between 310 to 330 mm, and mean temperatures in November are about 33°C and mean minimum in July are 16°C (Figures 1.6 and 1.7; Bureau of Meteorology 2013). Situated in the tropics, cyclones are common in the Gulf of Carpentaria. A total of 27 tropical cyclones passed within 100 km of the Wellesley Islands from1906 to 2006. While many cyclones pass by without causing major destruction each has the potential to affect the local ecologies (cf. Meehan 1982) and the coastal archaeological record (cf. Bird 1992; O'Connor 1989; Przywolnik 2002).

1.4 Thesis Structure

The results of this research and part of the thesis requirement were published in a number of peer-reviewed journals and presented in the following chapters. These chapters follow the general outline of each publication but have been reformatted for this thesis. Full citations of each publication are also included at the chapter beginning. In addition, several presentations resulting from this work were presented at professional meetings and in guest lectures in Australia and internationally (cf. Lowe et al. 2011 at the annual Australian Archaeological Association [AAA] Conference in Toowoomba, Australia; Rosendahl et al. 2012 at the annual AAA conference in Wollongong, Australia; Lowe 2013 guest lecture at the Institute of Rock Magnetism, University of Minnesota, USA; Lowe and Wallis 2013 at the Society of American Archaeology [SAA] conference in Hawaii, USA; Lowe et al. 2013 at the annual AAA conference in Coffs Harbor, Australia; and Wallis et al. 2014 at the Australasian Quaternary Association [AQUA] biennial conference in Mildura, Australia).

Chapter 2 examines the history and use of geophysical techniques in Australia and seeks to understand why their use in Australian archaeology is still rare. This review examines how factors including costs, time, instrument availability or lack of theoretical knowledge have contributed to the underutilisation of these methods to date. This chapter also discusses where and how archaeological geophysics have been applied in Australian contexts, what this discipline might offer in terms of addressing local research questions, and whether there is potential for Australian archaeologists to develop the skills necessary to conduct archaeological geophysics in the future as their international counterparts currently do. This chapter was published in *Australian Archaeology* in 2012 as a sole-authored paper.

Chapter 3 is a techniques paper that explores the causes of magnetic changes in the sedimentary deposit of a Pleistocene-aged rockshelter in the semi-arid zone of northwest Queensland. Rather than assuming that increases in magnetic susceptibility are the result of cultural activity, an experimental burning program, coupled with analysis of off-site samples, was undertaken to confirm that magnetically enhanced sediments in cultural deposits are a result of anthropogenic burning and not due to natural fires, pedogenesis or weathering. This chapter was submitted to *Geoarchaeology* in 2014 and is currently in review. Co-authors include James Shulmeister, Josh M. Feinberg, Tiina Manne, Lynley A. Wallis and Kevin Welsh. K.M.L. and L.A.W. organised this study. L.A.W. collected the archaeological and off-site sediment samples for analysis. K.M.L. designed the research, performed all the soil magnetic susceptibility laboratory work and analysis, and drafted the manuscript. J.M.F. assisted with the soil magnetic analysis and interpretation. All authors helped interpret the results and contributed to writing the paper.

Chapter 4 builds on the data presented in Chapter 3, integrating magnetic susceptibility and micromorphology with other sedimentary and archaeological data to understand the nature and persistence of human occupation at the aforementioned Pleistocene-aged rockshelter in northwest Queensland. Particular emphasis was on the relationship with changing climatic regimes. The stratigraphic homogeneity of many sandstone rockshelters in Australia, coupled with the limited understanding of LGM deposits has been a critical factor for understanding key Pleistocene sites. By using techniques that are effective for understanding anthropogenic inputs and complicated stratigraphies, such as magnetic susceptibility and micromorphology, this study has shown that these issues can be resolved. This chapter was submitted to *Quaternary Science Reviews* in 2014 and is currently in review. Co-authors include Susan Mentzer, Lynley A. Wallis and James Shulmeister. K.M.L. and L.A.W. organised and designed this study. L.A.W. collected the archaeological and off-site sediment samples for analysis, and completed all artefact and ochre analysis. K.M.L. performed all the sediment magnetic susceptibility and particle size laboratory work and analysis, and drafted the manuscript. S.M. conducted, processed and analysed all micromorphology data. J.S. provided the palaeoclimatic data and interpretation. All authors helped interpret the results and contributed to writing the paper.

Chapter 5 details how GPR was combined with archaeological excavation data using a GIS approach to identify numerous burials that were subsequently excavated in a sandstone rockshelter context in the Northern Territory of northern Australia. Results were analysed statistically to confirm that the association between rocks and burials was deliberate rather than random. This research highlights the importance of detailed data recording and integration when attempting to investigate and map complex archaeological sites. This chapter was published in *Archaeology in Oceania* in 2014. Co-authors include Lynley A. Wallis, Colin Pardoe, Ben Marwick, Chris Clarkson, Tiina Manne, Mike Smith and Richard Fullagar. K.M.L, L.A.W., C.C. and M.A.S. organised the initial GPR study. K.M.L. designed the research, collected and processed the GPR and GIS data, and drafted the manuscript. L.A.W. assisted with the GPR and GIS data collection, and supervised all burial excavations (both field and lab). C.P. conducted the skeletal analysis. B.M. completed the statistical analysis. All authors helped interpret the results and contributed to writing the paper.

Chapter 6 presents results from a pilot project incorporating a range of conventional sedimentary and archaeological analyses with magnetic susceptibility at three anthropogenic shell mounds from an island in the Gulf of Carpentaria (northern Australia) to assess site integrity and determine whether magnetic signatures were related to cultural or natural site formation processes. Analysis demonstrates that the mounds were repeatedly visited despite archaeological evidence, including radiocarbon dates, suggesting archaeologically ‘instantaneous’ deposition. This chapter was published in the *Journal of Archaeological Science* in 2014. Dan Rosendahl is first author, followed by author as second, co-authors include Lynley A. Wallis and Sean Ulm. D.R. and L.A.W. organised the initial study. D.R. collected the archaeological and off-site sediment samples for analysis and performed all the soil magnetic susceptibility laboratory work. K.M.L. assisted with the laboratory work and analyses, and processed the magnetic susceptibility data. D.R. and K.M.L. designed and drafted the manuscript. All authors helped interpret the results and contributed to writing the paper.

Chapter 7 presents the summary and conclusions of the thesis research, highlighting the issues discussed in the literature review and where we are today in Australian archaeology.

Appendix A presents the methods used for this thesis, paying specific attention to magnetic susceptibility and environmental magnetism theory and practice as well as GPR and geoarchaeological applications.

Appendix B contains all of the archaeological, geoarchaeological and geophysical data used for GS1.

Appendix C contains all of the magnetic analysis data generated for GS1 and was conducted at the Institute of Rock Magnetism, University of Minnesota.

Appendix B contains all of the archaeological, geoarchaeological and geophysical data for the Mornington Island sites: Guttapercha, Mala Katha and Munburlda.

References

Allen, J. 1994 Radiocarbon determinations, luminescence dating and Australian archaeology. *Antiquity* 68:339–343.

Allen, J. and J. F. O'Connell 2003 The long and the short of it: Archaeological approaches to determining when humans first colonised Australia and New Guinea. *Australian Archaeology* (57):5–19.

Anschuetz, K. F., R. H. Scheick and C. L. Scheick 2001 An archaeology of landscapes: Perspectives and direction. *Journal of Archaeological Research* 9(2): 157–211.

Aspinall, A., C. Gaffney and L. B. Conyers 2008 Archaeological Prospection – the first fifteen years. *Archaeological Prospection* 15(4):241–245.

Bird, M. K. 1992 The impact of tropical cyclones on the archaeological record: An Australian example. *Archaeology in Oceania* 27(2):75–85.

Birdsell, J. B. 1977 The recalibration of a paradigm for the first peopling of greater Australia. In J. Allen, J. Golson and R. Jones (eds), *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia, and Australia*, pp. 113–167. London: Academic Press.

Bowdler, S. 1977 The coastal colonisation of Australia. In J. Allen, J. Golson and R. Jones (eds), *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*, pp. 205–246. London: Academic Press.

Bowdler, S. 1990 50,000 year-old site in Australia – Is it really that old? *Australian Archaeology* 31:93.

Bowdler, S. 1991 Some sorts of dates from Malakunanja II: A reply to Roberts et al. *Australian Archaeology* 32:50–51.

Bowler, J. M., H. Johnston, J. M. Olley, J. R. Prescott, R. G. Roberts, W. Shawcross and N. A. Spooner 2003 New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421(6925):837–840.

Brown, P. 1997 Australian palaeoanthropology. In F. Spencer (ed.), *History of Physical Anthropology: An Encyclopedia*, pp. 138–145. New York: Garland Publishing.

Campana, S. and S. Piro (eds) 2009 *Seeing the Unseen: Geophysics and Landscape Archaeology*. London: Taylor and Francis Group.

Clark, A. 1996 *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Routledge.

Chaloupka, G. 1985 Chronological sequence of Arnhem Land plateau rock art. In R. Jones (ed.), *Archaeological Research in Kakadu National Park*, pp. 269-280. Special Publication 13. Canberra: Australian National Parks and Wildlife Service.

Conyers, L. B. and J. Leckebusch 2010 Geophysical archaeology research agendas for the future : Some ground-penetrating radar examples. *Archaeological Prospection* 123:117–123.

Conyers, L. B. 2011 Discovery, mapping and interpretation of buried cultural resources non-invasively with ground-penetrating radar. *Journal of Geophysics and Engineering* 8(3):S13–S22.

Dalan, R. A. 2001 A magnetic susceptibility logger for archaeological application. *Geoarchaeology* 16(3):263–273.

Dalan, R. A. 2008 A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: Recent developments and prospects. *Archaeological Prospection* 15:1–31.

Dalan, R. A. and S. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13(1):3–36.

David, B., R. G. Roberts, J. Magee, J. Mialanes, C. Turney, M. Bird, C. White, K. L. Fifield and J. Tibby 2007 Sediment mixing at Nonda Rock: Investigations of stratigraphic integrity at an early archaeological site in northern Australia and implications for the human colonisation of the continent. *Journal of Quaternary Science* 22(5):449–479.

Davidson, I. and W. Noble 1992 Why the first colonisation of the Australian region is the earliest evidence of modern human behaviour. *Archaeology in Oceania* 27:113–119.

East, J. T. 1996 Landform evolution. In C. M. Finlayson and I. von Oertzen (eds), *Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia*, pp. 37–55. Geobotany 23. London: Kluwer Academic Publishers.

Ellwood, B., F. B. Harrold, S. L. Benoist, P. Thacker, M. Otte, D. Bonjean, G. J. Long, A. M. Shahin, R. P. Hermann and F. Grandjean 2004 Magnetic susceptibility applied as an age-depth-climate relative dating technique using sediments from Scladina Cave, a late Pleistocene cave site in Belgium. *Journal of Archaeological Science* 31(3):283–293.

Ellwood, B. B., D. E. Peter, W. Balsam and J. Schieber 1995 Magnetic and geochemical variations as indicators of palaeoclimate and archaeological site evolution: Examples from 41TR68, Fort Worth, Texas. *Journal of Archaeological Science* 22(3):409–415.

Ellwood, B. B., K. M. Petruso, F. B. Harrold and J. Schuldenrein 1997 High-resolution paleoclimatic trends for the Holocene identified using magnetic susceptibility data from archaeological excavations in caves. *Journal of Archaeological Science* 24:569–573.

Farrand, W. R. 2001 Sediments and stratigraphy in rockshelters and caves: A personal perspective on principles and pragmatics. *Geoarchaeology* 16(5):537–557.

Franklin, N. R. and P. J. Habgood 2007 Modern human behaviour and Pleistocene Sahul in review. *Australian Archaeology* 65:1–16.

Gaffney, C. and J. Gater 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing.

Gibbs, M. and D. Gojak 2009 Remote sensing in an urban Australian setting. *Australian Archaeology* 68:45–51.

Gifford-Gonzalez, D. P., D. B. Damrosch, D. R. Damrosch, J. Pryor and R. L. Thunen 1985 The third dimension in site structure: An experiment in trampling and vertical dispersal. *American Antiquity* 50(4):803–818.

Grimes, K. G. 1979 *Mornington-Cape Van Dieman Queensland: 1:250,000 Geological Series Explanatory Notes*. Canberra: Australian Government Publishing Service.

Grimes, K. G. and I. P. Sweet 1979 *Westmoreland Queensland: 1:250,000 Geological Series Explanatory Notes*. Canberra: Australian Government Publishing Service.

Hein, K. A. A. 2002 Geology of the Ranger Uranium Mine, Northern Territory, Australia: Structural constraints on the timing of uranium emplacement. *Ore Geology Reviews* 20(3–4):83–108.

Herries, A. I. R. 2006 Archaeomagnetic evidence for climate change at Sibudu cave. *South African Humanities* 18:131–147.

Hiscock, P. 1990 Comment: How old are the artefacts at Malakunanja II? *Archaeology in Oceania* 25:122-124.

Hiscock, P. 2008 *Archaeology of Ancient Australia*. London: Routledge Taylor and Francis Group.

Hiscock, P. and L. A. Wallis 2005 Arid paradises or dangerous landscapes: A review of explanations for Paleolithic assemblage change in arid Australia and Africa. In P. Veth, M. Smith and P. Hiscock (eds), *Desert Peoples: Archaeological Perspectives*, pp. 58–77. Oxford: Blackwell.

Holliday, V. T. 2004 *Soils in Archaeological Research*. Oxford: Oxford University Press.

Hughes, P. J. and R. J. Lampert 1977 Occupational disturbance and types of archaeological deposits. *Journal of Archaeological Science* 4:135–140.

Johnson, J. K. (ed.) 2006 *Remote Sensing in Archaeology: An Explicitly North American Perspective.* Tuscaloosa: University of Alabama.

Jordanova, N., E. Petrovsky, M. Kovacheva and D. Jordanova 2001 Factors determining magnetic enhancement of burnt clay from archaeological sites. *Journal of Archaeological Science* 28:1137–1148.

Kamminga, J. and H. Allen 1973 *Report of the Archaeological Survey: Alligator Rivers Environmental Fact-Finding Study*. Darwin: Government Printer.

Keys, B. O. 2009 *Engrained in the Past: Using Geoarchaeology to Understand Site Formation Processes at the Gledswood Shelter 1 Site, Northwest Queensland*. Unpublished BArch (Honours) thesis, Department of Archaeology, Flinders University, Adelaide.

Latham, A. G. and A. I. R. Herries 2004 The formation and sedimentary infilling of the Cave of Hearths and Historic Cave complex, Makapansgat, South Africa. *Geoarchaeology* 19(4):323–342.

Lewis, D. J. 1988 *The Rock Paintings of Arnhem Land, Australia: Social, Ecological and Material Culture Change in the Post-Glacial Period*. BAR International Series S415. Oxford: Archaeopress.

Linford, N., P. Linford and E. Platzman 2005 Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames Valley, UK. *Journal of Archaeological* Science 32(7):1037–1043.

Magee, J. W., J. M. Bowler, G. H. Miller and D. L. G. Williams 1995 Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 113:3–42.

Magee, J. W. and G. H. Miller 1998 Lake Eyre palaeohydrology from 60 ka to the present: Beach ridges and glacial maximum aridity. *Palaeogeography, Palaeoclimatology, Palaeoecology* 144:307–329.

Maher, B. A. 2011 The magnetic properties of Quaternary aeolian dusts and sediments, and their palaeoclimatic significance. *Aeolian Research* 3(2):87–144.

Maki, D., J. A. Homburg and S. D. Brosowske 2006 Thermally activated mineralogical transformations in archaeological hearths: Inversion from maghemite Fe_2O_4 phase to haematite Fe_2O_4 form. *Archaeological Prospection* 13:207–227.

Marwick, B. 2002 Milly's Cave: Evidence for human occupation of the inland Pilbara during the Last Glacial Maximum. In S. C. Ulm, C. Westcott, J. Reid, A. Ross, I. Lilley, J. Prangnell and L. Kirckwood (eds), *Barries, Borders, Boudnaries: Procedings ofs the 2001 Australian Archaeological Association Annual Conference,* pp. 21–33. Tempus 7. St Lucia: Anthropology Musem, The Univeristy of Queensland.

Marwick, B. 2005 Element concentrations and magnetic susceptibility of anthrosols: Indicators of prehistoric human occupation in the inland Pilbara, Western Australia. *Journal of Archaeological Science* 32:1357–1368.

May, S. K., P. S. C. Taçon, D. Wesley and M. Travers 2010 Painting history: Indigenous observations and depictions of the 'Other' in northwestern Arnhem Land, Australia. *Australian Archaeology* 71:57–65.

McQuade, C. V., J. T. Arthur and I. .J. Butterworth 1996 Climate and hydrology. In C. M. Finlayson and I. von Oertzen (eds), *Landscape and Vegetation Ecoogy of the Kakadu Region, Northern Australia*, pp. 17–35. Geobotany 23. London: Kluwer Academic Publishers.

Meehan, B. 1982 *Shell Bed to Shell Midden.* Canberra: Australian Institute of Aboriginal Studies.

Meterology, Bureau of 2013 *Monthly Mean Maximum Temperature – Richmond Post Office*. Melbourne: Commonwealth of Australia.

Miller, G. H., J. M. Magee and A. J. T. Jull 1997. Low latitude glacial cooling in the Southern Hemisphere from amino acids in emu eggshells. *Nature* 385:241–244.

Mitchell, S. 1994 *Culture Contact and Indigenous Economies on the Coburg Peninsula*. Unpublished PhD thesis, Department of Anthropology, Northern Territory University, Darwin.

Moffat, I., L. A. Wallis, A. Beale and D. Kynuna 2008 Trialing geophysical techniques in the identification of open Indigenous sites in Australia: A case study from inland northwest Queensland. *Australian Archaeology* 66:60–63.

Morwood, M. J. 1992 Changing art in a changing landscape: A case study from the upper Flinders River region of the north Queensland highlands. In J. McDonald and I. P. Haskovec (eds), *State of the Art: Regional Rock Art Studies in Australia and Melanesia*, pp. 60–70. Melbourne: Australian Rock Art Research Association.

Mulvaney, D. J. and J. Kamminga 1999 *Prehistory of Australia.* Washington and London: Smithsonian Institution Press.

Murphy, L. R. and R. D. Mandel 2012 Geoarchaeology and paleoenvironmental context of the Burntwood Creek rockshelter, high plains of northwestern Kansas, U.S.A. *Geoarchaeology* 27(4):344–362.

Nanson, G. C., T. J. East and R. G. Roberts 1993 Quaternary stratigraphy, geochronology and evolution of the Magela Creek catchment in the monsoon tropics of northern Australia. *Sedimentary Geology* 83(3–4):277–302.

Needham, R. S. 1988 *Geology and Mineralization of the South Alligator Valley Mineral Field, Northern Territory*. Canberra: Bureau of Mineral Resources.

Needham, R. S. and P. G. Stuart-Smith 1984 *Geology of the Pine Creek Geosyncline, Northern Territory*. Canberra: Bureau of Mineral Resources.

Nielsen, A. E. 1991 Trampling the archaeological record: An experimental study. *American Antiquity* 56(3):483–503.

O'Connell, J. F. and J. Allen 1998 When did humans first arrive in greater Australia and why is it important to know? *Evolutionary Anthropology* 6:132–146.

O'Connell, J. F. and J. Allen 2004 Dating the colonization of Sahul (Pleistocene Australia–New Guinea): A review of recent research. *Journal of Archaeological Science* 31:835–853.

O’Connor, S. 1989 Contemporary island use in the west Kimberley, Western Australia, and its implications for archaeological site survival. *Australian Aboriginal Studies* 2:25–31.

O'Connor, S., P. Veth, and A. Barham 1999 Cultural versus natural explanations for lacunae in Aboriginal occupation deposits in northern Australia. *Quaternary International* 59:61–70.

Perry, R. A. and M. Lazarides 1964 Vegetation of the Leichhardt-Gilbert area. In R.A. Perry (ed.), *General Report on Lands of the Leichhardt-Gilbert Area, Queensland, 1953–54*. Land Research Series. Melbourne: Commonweatlh Scientific and Industrial Research Organisation.

Petherick, L. M., P. T. Moss and H. A. McGowan 2011 Climatic and environmental variability during the termination of the last glacial stage in coastal eastern Australia: A review. *Australian Journal of Earth Sciences* 58(6):563–577.

Przywolnik, K. 2002 Coastal sites and severe weather in Cape Range Peninsula, northwest Australia. *Archaeology in Oceania* 37(3):137–153.

Rapp, G. R. Jr. and C. L. Hill 1998 *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.

Richardson, N. 1992 Conjoin sets and stratigraphic integrity in a sandstone rockshelter: Kenniff Cave (Queensland, Australia). *Antiquity* 66:408–418.

Richardson, N. 1996 Seeing is believing: A graphical illustration of the vertical and horizontal distribution of conjoined artefacts using DesignCAD 3D. In S. Ulm, I. Lilley and A. Ross (eds), *Australian Archaeology ’95: Proceedings of the 1995 Australian Archaeological*

Association Annual Conference, pp. 81–95. Tempus 6. St. Lucia: Anthropology Museum, Department of Anthropology and Sociology, University of Queensland.

Richardson, N. 2010 *Conjoin Sets, Stratigraphic Integrity and Chronological Resolution at Keniff Cave, Queensland*. Unpublished MPhil thesis, School of Archaeology and Anthropology, The Australian National University, Canberra.

Roberts, R. G., R. Jones and M. A. Smith 1990a Stratigraphy and statistics at Malakunanja II : Reply to Hiscock. *Archaeology in Oceania* 25(3):125–129.

Roberts, R. G., R. Jones and M. A. Smith 1990b Thermoluminescence dating of a 50,000-year old-human occupation site in northern Australia. *Nature* (345):153–56.

Rosendahl, D. 2012 *The Way it Changes Like the Shoreline and the Sea: The Archaeology of the Sandalwood River, Mornington Island, Southeast Gulf of Carpentaria, Australia.* Unpublished PhD thesis, School of Architecture, The University of Queensland, St Lucia.

Smart, J. 1973 *Gilberton, Queensland 1:250,000 Geological Series*. Explanatory Notes, Sheet SE54-16. Canberra: Australian Government Publishing Service.

Smith, M. A. 1989 The case for a resident human population in the Central Australian ranges during full glacial aridity. *Archaeology in Oceania* 24(3):93–105.

Smith, M. A. 1993 Biogeography, human ecology and prehistory in the sandridge deserts. *Australian Archaeology* (37):35–50.

Smith, M. A. and N. D. Sharp 1993 Pleistocene sites in Australia, New Guinea and island Melansesia: Geographic and temporal structure of the archaelogical record. In M.A. Smith, M. Spriggs and B. Fankhauser (eds), Sahul in Review: *Pleistocene archaeology in Australia, New Guinea and Island Melansesia*, pp. 37–59. Canberra: The Australian National University.

Smith, M. A., J. R. Prescott and M. J. Head 1997 Comparison of ^{14}C and luminescence chronologies at Puritjarra rock shelter, Central Australia. *Quaternary Science Reviews* 16(3–5):299–320.

Stein, J. K. and W. R. Farrand 2001 *Sediments in Archaeological Context*. Salt Lake City: University of Utah Press.

Stern, H., G. de Hoedt and J. Ernst 2004 Objective classification of Australian climates. *Australian Meteorological Magazine* 49:87–96.

Stockton, E. D. 1973 Shwa’s Creek Shelter: Human displacement of arefacts and its significance. *Mankind* 14:112–117.

Straus, L. G. 1990 Underground archaeology: Perspectives on caves and rockshelters. *Archaeological Method and Theory* 2:255–304.

Taçon, P. S. C.1993 Regionalism in the recent rock art of western Arnhem Land, Northern Territory. *Archaeology in Oceania* 28:112–20.

Thompson, R. and F. Oldfield 1986 *Environmental Magnetism*. London: Allen and Unwin.

Veth, P. 1989 Islands in the interior: A model for the colonization of Australia's arid zone. *Archaeology in Oceania* 24(3):81–92.

Veth, P. 1993 The Aboriginal occupation of the Montebello Islands, north-west Australia *Australian Aboriginal Studies* 2(1993):39–50.

Wade, V., L. A. Wallis, and Woolgar Valley Aboriginal Corporation 2011 Style, space and social interaction: An archaeological investigation of rock art in inland north Queensland, Australia. *Australian Archaeology* 72:23–34.

Wallis, L. A., K. Fitzsimmons, K. M. Lowe, B. Keys, I. Moffat, X. Carah, N. Wright and S. Mentzer Unpublished data. Site report on Gledswood Shelter 1. The University of Queensland, St. Lucia.

Wallis, L. A., B. Keys, I. Moffat and S. Fallon 2009 Gledswood Shelter 1 : Initial radiocarbon dates from a Pleistocene aged rockshelter site in northwest Queensland. *Australian Archaeology* 69:71–74.

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

Ward, I. A. K., R. L. K. Fullagar, T. Boer-Mah, L. M. Head, P. S. C. Taçon and K. Mulvaney 2006 Comparison of sedimentation and occupation histories inside and outside rock shelters, Keep-River region, northwestern Australia. *Geoarchaeology* 21:1–27.

Ward, I. 2004 Comparative records of occupation in the Keep River region of the eastern Kimberley, northwestern Australia. *Australian Archaeology* 59:1–9.

Watchman, A., I. Ward, R. Jones and S. O’Connor 2001 Spatial and compositional variations within finely laminated mineral crusts at Carpenter's Gap, an archaeological site in tropical Australia. *Geoarchaeology* 16(7):803–824.

Waters, M. R. 1992 *Principles of Geoarchaeology: A North American Perspective*. Tucson: The University of Arizona Press.

Welch, D. 1995 Beeswax rock art in the Kimberley, Western Australia. *Rock Art Research* 12(1): 23–28.

Wesley, D. 2013 Firearms in Arnhem Land rock art. *Rock Art Research* 30(2):235–247.

Wesley, D., J. McKinnon and J. Raupp 2012 Sails set in stone: A technological analysis of non-Indigenous watercraft rock art paintings in north western Arnhem Land. *Journal of Maritime Archaeology* 7(2):245–269.

Williams, M., E. Cook, S. van der Kaars, T. Barrows, J. Shulmeister and P. Kershaw 2009 Glacial and deglacial climatic patterns in Australia and surrounding regions from 35 000 to 10 000 years ago reconstructed from terrestrial and near-shore proxy data. *Quaternary Science Reviews* 28(23–24):2398–2419.

CHAPTER 2

REVIEW OF GEOPHYSICAL APPLICATIONS IN AUSTRALIAN ARCHAEOLOGY

Chapter 2 is reproduced from the article in *Australian Archaeology* and is part of the thesis literature review. It has been reformatted for this thesis chapter.

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. Australian Archaeology 74:71–84.

2.1 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, if factors such as costs, time, instrument availability or lack of theoretical knowledge are reasons these methods have been underrepresented in archaeological investigations to date. With the 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 geophysics as their international counterparts in the future.

2.2 Introduction

Interdisciplinary studies are extremely useful for investigating archaeological sites and there has been 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 interactions with the environment. Likewise, archaeological geophysics techniques have been applied routinely to map sites, but also to address more sophisticated research questions (e.g. Conyers and Leckebusch 2010; Dalan, et al. 2003; Gaffney and Gater 2003:23; Johnson 2006). Archaeological geophysical studies have been so prolific that a specialist journal (Archaeological Prospection) as well as 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 (Aspinall et al. 2008a). Geophysical methods have become part of the standard archaeological science teaching regime in British universities and in 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 interest in using these methods to investigate Australian archaeological sites, driven by factors including their non-destructive nature and their capacity to rapidly assess subsurface archaeological remains. This affords potential benefits in the cultural heritage management arena, and 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 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 the potential advantages, these methods have been so underrepresented in Australian archaeological investigations to date given that they were first introduced here in the 1970s.

2.3 Geophysics and Landscape Archaeology

As geophysics are so widely used for investigating ‘landscapes’, it is appropriate first to examine what is meant by this highly variable 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 definitions provided by Roberts (1987:77) as ‘the physical framework within which human societies exist’. Others define 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) and is 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), who was interested in the interplay between culture and the environment. Butzer applied a systems approach to analyse the dynamic interactions between societies and their environments (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, and concepts that focus on social and symbolic aspects leads to two different ways to approach the analysis of landscapes (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 experience (individual) and attempts to investigate how landscapes are perceived with meaning 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 the cultural and natural environment (Anschuetz et al. 2001:157–158) and, in the broadest sense, involve the physical alteration of the latter (Lawrence and Low 1990:454): it is these physical alterations that can be studied through archaeological geophysics. Geophysical techniques are well-suited for detecting cultural features such as buried architectural features, 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. 2008a) 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 Gater 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 Gater 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 house structure 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 differences in physical and chemical properties can be measured and mapped with geophysical instruments, thus leading to a better understanding of spatial relationships and depositional environments between buried features and the landscape.

2.4 Common Geophysical Techniques used in Archaeology

Geophysical applications in archaeology did not become popular until the 1970s with the emergence of processual archaeology, and its greater emphasis on scientific applications and rigour (Bevan and Kenyon 1975; Fischer 1980; Scollar 1971; 1986; Weymouth 1979). 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: electrical resistance; electromagnetic conductivity; magnetometry; and GPR. However, magnetic susceptibility, a technique not frequently used as the others will also be discussed. With the exception of magnetometry, all are active methods, meaning they send signals into sedimentary deposits and map the physical and chemical response of the deposit. As part of this review, the following section describes briefly each of the methods and how they are used in archaeology. This paper's intentions are not to provide a detailed theory of these methods, rather an overview of their theoretical framework as it relates to archaeological prospection.

2.4.1 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 Gater 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 2.1).

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 m, 0.50 m or 1.0 m apart and manifested in any number of arrays. The two most common being 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 Gater 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 has been applied to archaeology with encouraging results, especially in the last decade (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 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 such as tells containing deeply buried monumental structures (e.g. Casana et al. 2008). However, it can also be used to map smaller, shallower features such as graves (Figure 2.2) (Stringfield et al. 2008). Widely-spaced electrodes allow measurements to be taken at greater depths, while narrowly spaced electrodes offer higher resolution near the surface.

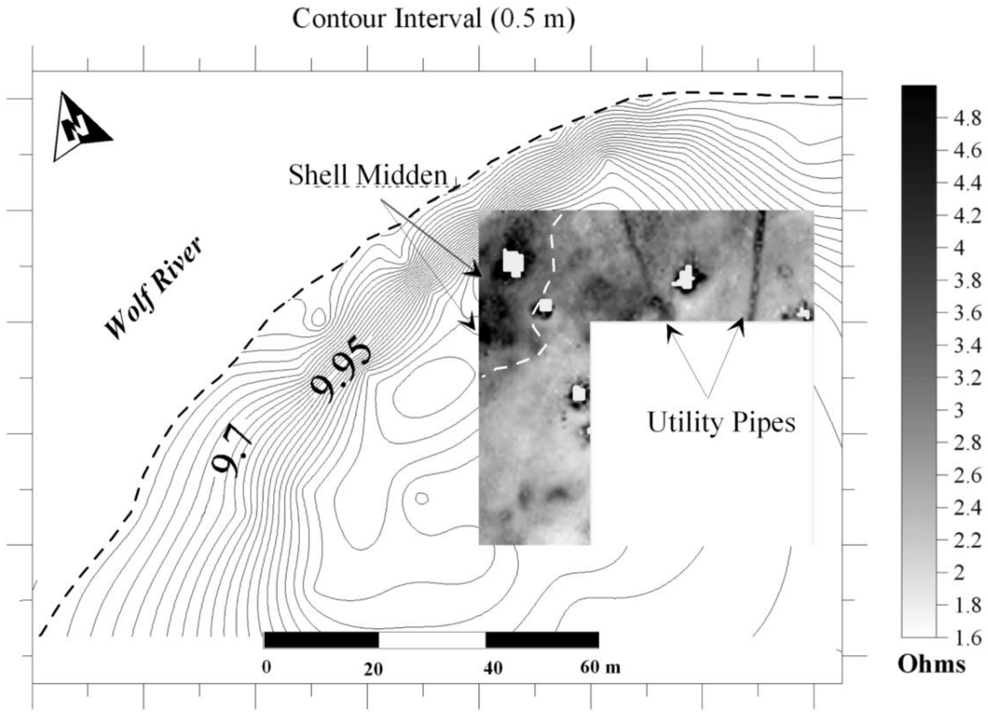

Figure 2.1 An example of a resistance image from the Oak Grove site (22HR502), a Middle Woodland to Late Mississippian (ca AD 400–1240) shell midden site located on a bluff overlooking the Wolf River. High resistance areas like shell midden deposits are shown in dark grey and the dotted white line indicates the shell middens inland extent (Lowe et al. 2010).

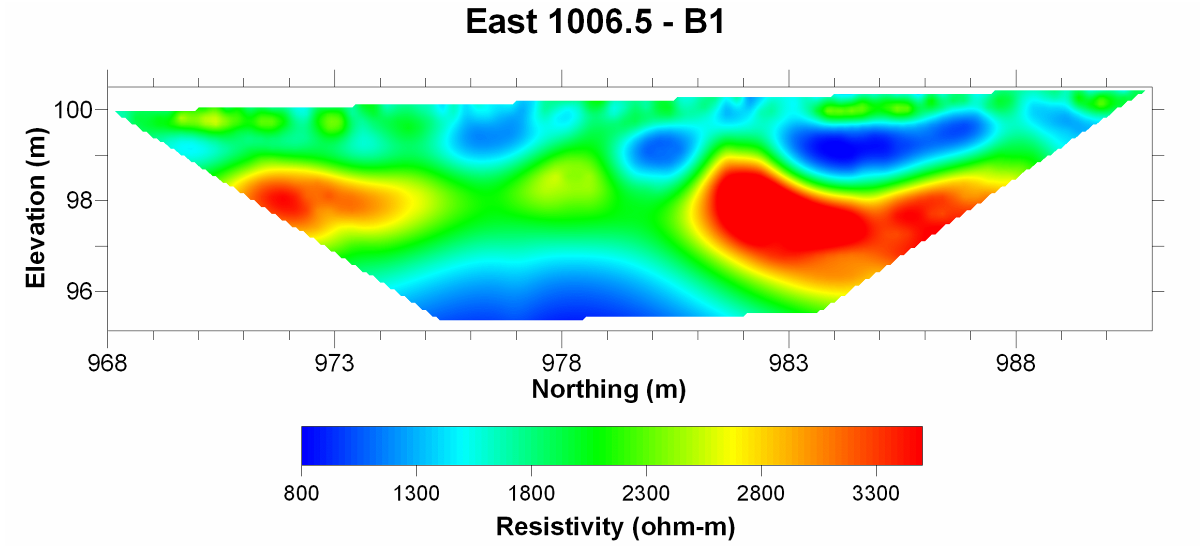

Figure 2.2 An example of electrical resistance tomography on the historic St. Michaels Cemetery in Pensacola, Florida, USA. Low resistivity anomalies located at ca 976.5 and 980 north indicate unmarked graves and the long low resistivity anomaly between 983 and 987 north could also indicate a row of graves (Stringfield et al. 2008). Image courtesy of Aaron Fogel.

2.4.2 Electromagnetic conductivity

Another active method is electromagnetic conductivity (EM). EM or ‘induction meters’ are 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 soil. They work 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 will be 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 plowed mounds (Figure 2.3).

2.4.3 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 radar wave continues downward until parts of it too 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 transmission of the wave much deeper (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 2.4).

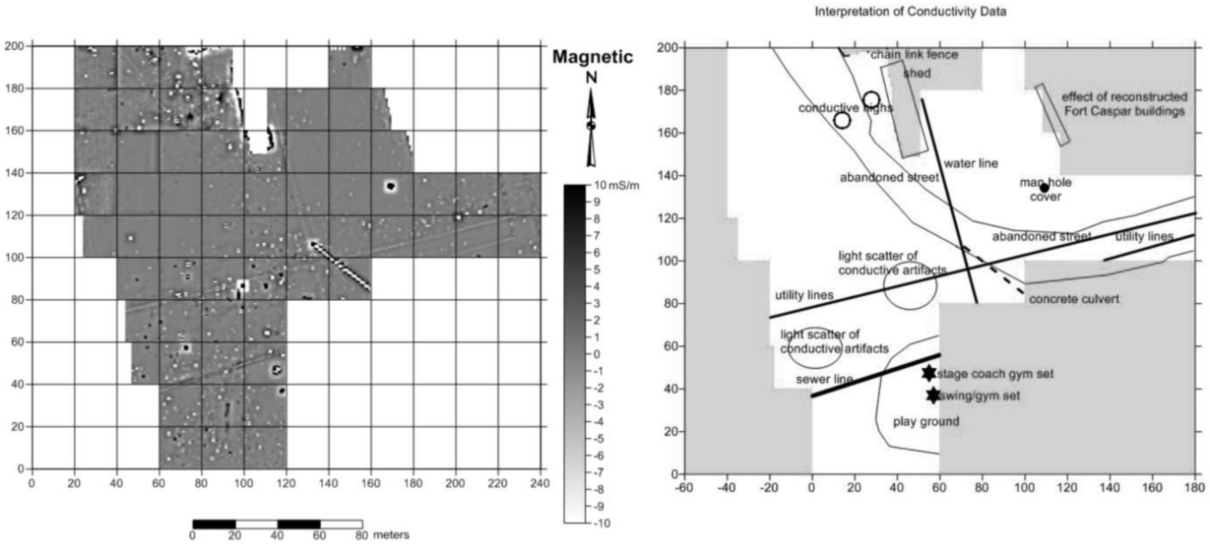

Figure 2.3 **(Left) An example of an electromagnetic conductivity image of the Fort Caspar 1865 military post. (Right) Interpretation of the image showing modern disturbances as well as an abandoned street and two light scatters, probably metal artefacts, in the general vicinity of a demolished house and a 19th century fort (DeVore 1988). Images courtesy of Steve DeVore.**

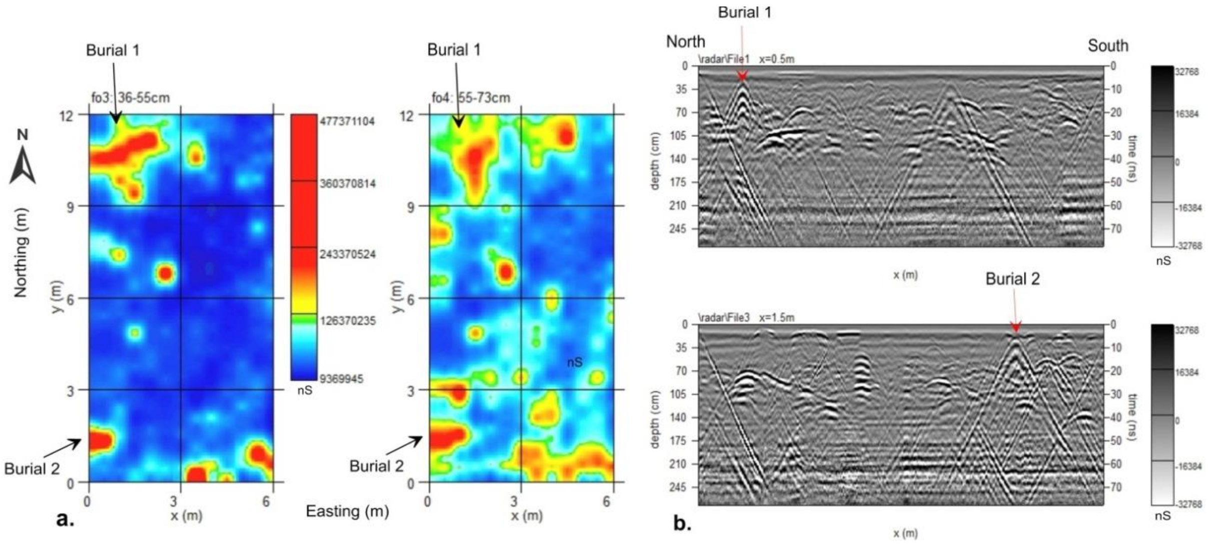

Figure 2.4 **An example of a GPR image of the Foley Plot located in historic Krebs Cemetery. This cemetery is part of the historic La Pointe Krebs House, ca 1700s. GPR was used to located unmarked graves that had been disturbed (headstones removed) from Hurricane Katrina: (a) is an amplitude slice-map showing the location of two burials; (b) a GPR reflection profile showing the two burials identified in the amplitude slice map (Lowe 2011).**

2.4.4 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. 2008b; 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 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. Gradiometers do not allow for the measurement of depth, only a gradient: 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). However, 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 meaning that magnetisation remains after the process that generated it (such as hearths and ditches), graves associated with metal (such as caskets, headstones or funerary objects) and areas of mounded topsoil and pits that have enhanced magnetic susceptibility (Figure 2.5) (Aspinall et al. 2008b; Gaffney and Gater 2003; Witten 2006).

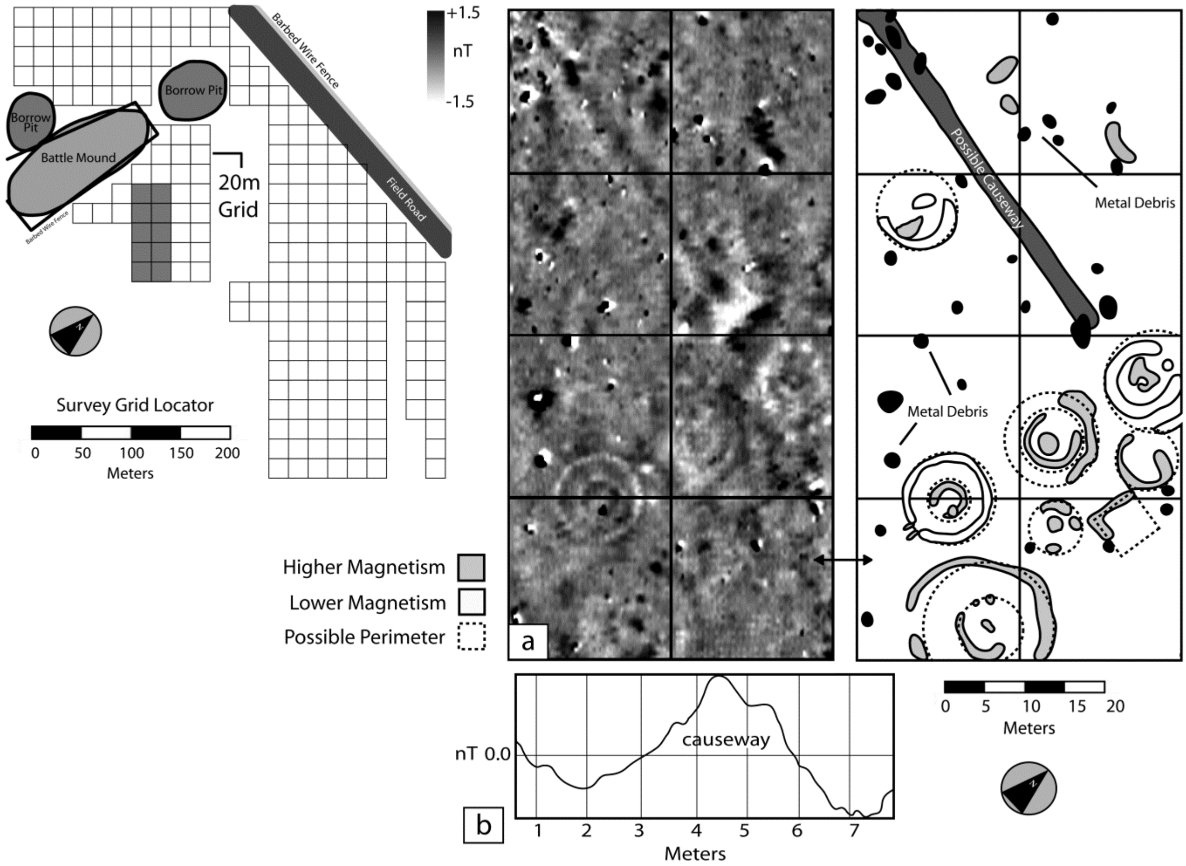

Figure 2.5 **A comparison of circular anomalies at the Battle Mound site (3LA1), a Middle-Late (ca AD 1200–1700) Caddo mound site: (a) magnetic gradiometry image from an area directly east of the large platform mound; (b) graph representation of a single traverse of magnetic gradiometry data over an area 200 m east of the mound showing a causeway. Image courtesy of Duncan McKinnon.**

2.4.5 Magnetic Susceptibility

Magnetic susceptibility could potentially be considered a fifth geophysical technique since it uses induced magnetisation, though it is generally discussed under electromagnetic conductivity or magnetometry in archaeological prospection. Magnetic susceptibility 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, magnetic susceptibility measures the permanent magnetisation of that field after it has been magnetised. Interestingly, magnetic susceptibility instruments can cover large areal surveys, using the IP component in EM instruments as previously discussed and they can measure finer increments in both down-hole and lab based applications (Figure 2.6). Archaeologically, magnetic susceptibility has been used to locate pits and ditch features, to identify burnt objects and to define buried cultural layers. It has also been used to map features vertically, 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 (Figure 2.7) (Dalan 2008).

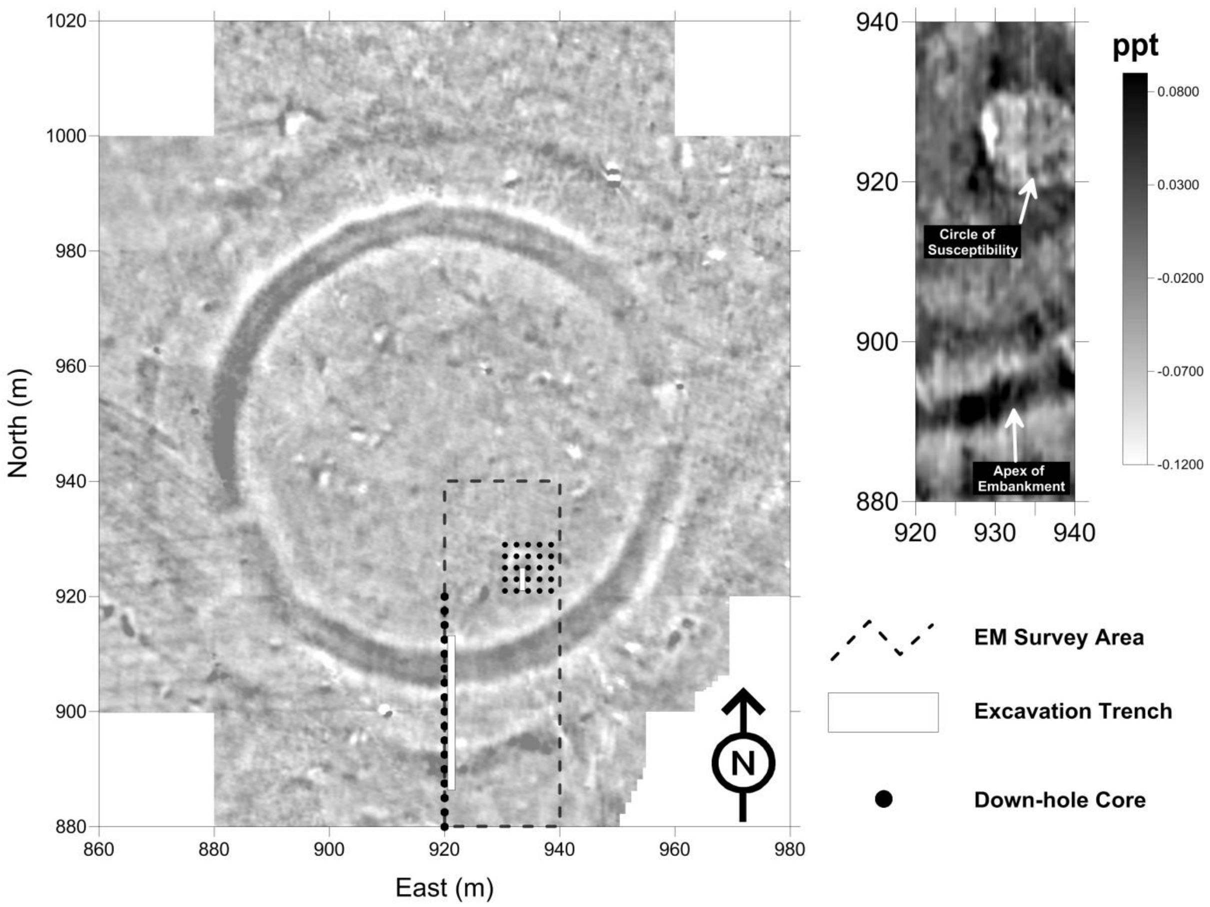

Figure 2.6 **A multistage geophysical approach at the LeBus Circle earthwork. (Left) A gradiometer image displayed at 50% opacity showing the circular earthwork and the location of down-hole magnetic susceptibility cores as black dots. (Right) A magnetic susceptibility image showing a circular anomaly with high susceptibility within the earthwork. Image courtesy of Edward R. Henry.**

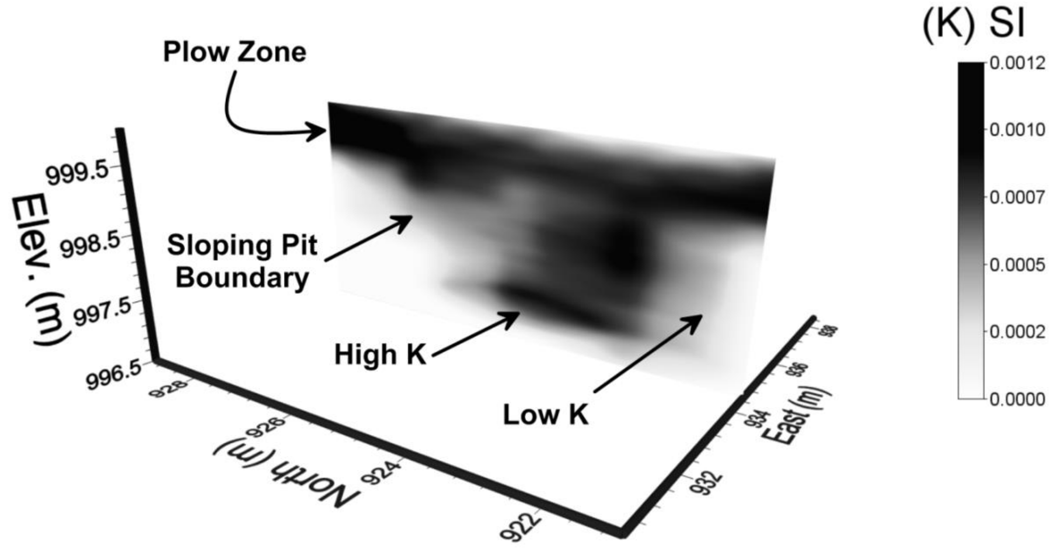

Figure 2.7 **A north-south profile of down-hole magnetic susceptibility through the centre of the circular anomaly or area of high susceptibility within the earthwork, also defined as a pit feature (refer to down-hole cores location from previous figure). Image courtesy of Edward R. Henry.**

2.5 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 such prospecting was becoming more common in Europe and North America. The first geophysical applications in Australian archaeology were undertaken by John Stanley (1975) from the University of New England. Working with archaeological colleagues, Stanley conducted several tests to determine whether a magnetometer could identify hearths and shell middens in the landscape and if it 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 substantial enough to cause detectable physical and chemical differences in the landscape (Tite 1972b: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. Here Stanley and colleagues demonstrated that the much cheaper (at approximately one-quarter the price) proton precession was much slower (taking 10 measurements per minute) than the caesium vapour magnetometer (which took 3,000 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 buried in dune deposits. Their work demonstrated that vessels with both high and low magnetic signals could be detected with magnetometry, even in areas that contained naturally magnetic materials like sands and basalt rocks, and that magnetometry 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 suite of technologies previously piloted. Ranson and Egloff (1988) demonstrated the applicability of the Gossen Geohm 3 resistivity meter via two case studies, one for locating graves in cemeteries and the other for identifying landscape features at an historic site. In the former, unmarked graves in a culturally sensitive Aboriginal cemetery, Wybalenna Cemetery in southern Australia, were identified using non-invasive geophysical techniques which proved successful because burials contain a different soil structure that contrasts with that surrounding them. In their second study, Ranson and Egloff (1988:64) used resistance to locate old paths, carriageways and gardens at the Port Arthur Historic Site in 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 instrument and data processing methods, 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 a 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 the re-development of the site, proposing that their approach was 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. As for their magnetic data, although they identified 17 anomalies, they also encountered a lot of noise (interference from power lines and iron roofs) during survey, which may have affected their results. Since no anomalies were investigated through excavation as part of their study, their determination as to the origins of the magnetic anomalies (i.e. whether they were modern noise or caused by 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 and that means some techniques are much better than others for use in urban settings.

Australian GPR applications continued with work conducted by Randolph et al. (1994) and Yelf and Burnett (1995) who both used the method for locating unmarked graves. Like Ranson and Egloff (1988) before them, Randolph et al. (1994) required a non-invasive method for locating burials in an Aboriginal prisoner cemetery located on Rottnest Island in southwest Australia. Likewise, Yelf and Burnett (1995) used the same approach for locating two Aboriginal cemeteries at Bundulla in 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 to assist their data interpretation, a critical factor in subsequently allowing them to identify unmarked burials at the cemetery of interest. While 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.

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. Bladon et al. 2011; 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 2013; Wallis et al. 2008; Yelf and Burnett 1995). This was 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 between grave fill sediments compared with surrounding soils due to changes in the physical properties or soil moisture content. 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 quite complimentary in the burial detection at the Ebenezer Mission cemetery in western Victoria. For Stanger and Roe (2007:49) neither GPR nor resistance methods were as successful as magnetometry at detecting burials at a 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 locating 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 the 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 due to the presence of high levels of contemporary metal in the survey area overshadowing the historic data of interest (cf. Hall and Yelf 1993). Yet this is not always the case for historic sites, as Brooks et al. (2009:41) found magnetometry to be useful for locating surviving 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 magnitudes) and management of hearths. A problem in hearth studies is the difficulty of recognising heat-fractured or affected rocks at 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 hearth types identified on the surface during a reconnaissance survey in southeastern 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 made during pedestrian survey. In turn, they then used those types to map and classify their magnetic signatures by looking at the differences between the site’s gradiometer reading (background) and the hearth gradiometer reading. They demonstrated that the densest concentrations of heat-fractured hearth stones produced the highest gradiometer values while lower concentrations produced low values (Fanning et al. 2009:21–22). However, the instrument was incorrectly zeroed at each hearth location making it difficult to accurately classify hearth signatures, as the collected readings would be inconsistent. Nevertheless, Fanning et al. (2009) made an attempt to use geophysics as a way to investigate site integrity based on magnetic signatures, 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 though 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 instead of 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 factors, 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. Magnetic susceptibility 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 demonstrated 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 laboratory-based methods using magnetic susceptibility to characterise and understand magnetic anomalies, features and mineralogies, with most being undertaken to investigate sediments and culturally enhanced or modified soil layers in rockshelter sites (Keys 2009; Marwick 2005). Other innovative magnetic susceptibility 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, magnetic susceptibility studies have been used to understand questions concerning the nature of geophysical anomalies themselves (Moffat et al. 2010). By combining magnetic susceptibility 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.

2.6 Discussion

A shift from testing the efficacy of geophysical techniques to using them as non-invasive methods to assist in archaeological 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 the present. In the 1970s, prices to purchase a magnetometer ranged from $1,600 to $7,000 (Connah et al. 1976) – today they range from $10,000 to $50,000, cost ranges comparable for most geophysical equipment. At this time, 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 still concerned with establishing such basic information as when Australia was first colonised by people (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. 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 general low demand for these methods.

The time required to conduct geophysical surveys was an important early consideration, though recent improvements in technology have greatly reduced the time necessary for data collection and post-fieldwork data processing. Survey areas that can be completed in a half-day could have taken up to three days to survey in the 1970s – clearly an impediment to its 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 type of sophisticated, often three-dimensional, geophysical maps we are accustomed to today. 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 maps, which while useful for producing ‘archaeologist-friendly’ plots of geophysical data required considerable data processing time (Clark 1996; Gaffney 2008). Contemporary computing software and processing speeds have greatly decreased geophysical processing 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 to processual archaeology as was emerging elsewhere at this time (Binford 1968; Caldwell 1959; Willey and Phillips 1955).

Instrument availability is another reason for its 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 geophysics instruments suitable for detecting subtle archaeological features are not 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 business are distributors, rather than manufactures, 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 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 their limitations and challenges 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 and understanding of the method allows a practitioner to understand why features may not be detectable using particular instrumentation. As described earlier, a lack of understanding of geophysical methods in some work conducted to date on Australian sites is evident. This includes 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 perceived primarily as an investigative technique, meaning its used simply to map sites rather than a research tool, used to help answer questions about human behaviour (Brooks et al. 2009; Hall and Yelf 1993; Moffat et al. 2008; Powell 2004; Wallis et al. 2008).

Almost all of the Australian studies discussed above reveal difficulties in confidently discerning archaeological features without test excavating, a factor in all remote prospecting. However, limitations in data processing and software (Ranson and Egloff 1988:71) or inexperience in data interpretation further amplified the difficulty of recognising features. In many instances, the resulting geophysical maps are limited and difficult to interpret. For instance, most of the GPR results in Australia 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 programs used more for deep geophysical exploration and not shallow exploration, leading to a disadvantage in visual representation and data interpretation.

The inherently ancient nature of Australia’s landscape is also a potential reason for the lack of archaeological geophysical applications here. Climatic changes, especially in the last 50,000 years, have caused significant changes in Australia’s landscape uniquely different to those experienced elsewhere. As conditions became cooler and drier leading into the LGM period (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 Australia’s interior (Barrows et al. 2002; Bowler 1973; Hesse and McTainsh 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 (i.e. the Mississippi River in North America), are rare and thus Australian depositional environments are limited. Even in cases where limited sedimentary sequences exist, much of the archaeological material is visible on the surface and thus geophysics is 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 buried sites affected by these past 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 magnetics susceptibility, 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 does 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. (2008a: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 the journal *Archaeological Prospection*. For instance, Lindsay et al. (2010) used magnetometry to investigate socio-political change on Late Bronze Age settlements in northwestern Armenia and demonstrated that domestic and institutional remains discovered initially in the geophysical data and later in excavations continued to borrow earlier architectural traditions from the Middle Bronze Age. Further increases in 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 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 (e.g. original soil layer, floor construction, occupational layer and post-abandonment soil formation) and functionality (e.g. cooking and food preparation, tool manufacture and waste disposal).

Lowe and Fogel's (2010) integration of three geophysical methods (resistance, magnetometry and down-hole magnetic susceptibility) 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 in the aforementioned studies in Australia is very unlikely, similar geophysical techniques, geochemical analyses and soil micromorphology – to look at site functionality could be used on any type of Australian site, whether 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 or 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 additional technology, like Real-Time Kinematic-GPS with geophysical instruments provides a level of spatial control that allows geophysical data to be linked to broader GIS frameworks. Some examples include the recent developments and prospects for magnetic susceptibility 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; Petronille et al. 2010). Similar studies might profitably be applied to a number of 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 electromagnetic 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 nature (i.e. earthen mounds or extinct channels).

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 like 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 use 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 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 (Conyers et al. 2008). By using this method to map extinct channels, this study demonstrated that particular areas on the channels may be more probable locations for human occupation. While studies such as these may be a long way off in Australia archaeology, they do demonstrate the potential, particularly with respect to the latter example in regards 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 were 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.

2.7 Moving Forward: Archaeological Geophysics and Landscape in Australia

Technological advances in instrumentation elsewhere have provided a wide variety of resources to aid in basic data collection and analysis, yet these practices are still limited in Australian archaeology. Undoubtedly one of the main factors inhibiting the use of archaeological geophysics in Australia to date has been a general lack of familiarity with these methods and a corresponding lack of realisation as to how they might be profitably applied 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 (i.e. internet, publications and television programs such as *Time Team*) to the success of geophysical applications on archaeological sites in other areas of the world. Perhaps just as importantly, interest has escalated quite significantly as a result of an archaeological prospection short course now offered through Flinders University and several university based archaeology departments investing in purchasing suites of geophysical equipment (e.g. James Cook University, Sydney University, The Australian National University and The University of Queensland). 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 the opportunity to learn directly from experts more about these applications and how they can be applied to their research. Furthermore, 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 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. Geophysics maps both the natural and cultural physical changes at sites, and regardless of whether these changes were large, such as for 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 settled themselves on the landscape and made use of it in multitudes of ways through their social and cultural beliefs and actions.

For Australian archaeologists, the next step would be to determine whether they are ready to develop the skills necessary to conduct geophysical surveys themselves or if they would consider teaming up with other disciplines like geology or geophysics to understand Australia’s archaeological landscape. Despite its underutilisation currently, I believe there is potential to train Australian archaeologists in these methods or to a lesser extent, inform them on how geophysics can be used in their archaeological research given the direction it is now heading. The early 1990s brought out this opportunity for archaeologists to become practitioners in geophysical prospection. With trial and error, time and knowledge, it has now become a norm in most archaeological research. While it is equally important for archaeologist to team up with other disciplines, the fact that geophysical training is possible, has made significant advances in the field of archaeology. Steps towards a greater use of geophysics 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 been incorporating multiple disciplines and proxies to assist in their interpretations about Indigenous cultures, site formation processes and environmental change. By joining their international counterparts, Australian archaeologists can show how this integration can also be used in the understanding of the intra- and inter-site analysis of features within a site. Multidisciplinary approaches such as these, allows one to assess and perhaps reconstruct 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 grow, a better understanding will be gained about human cultural behaviour in the Australian landscape.

Acknowledgements

I would like to thank all those who have supported and contributed towards this review. This includes Lynley Wallis, Jamie Shulmeister and Ian Moffat for their comments, recommendations and advice. I would also like to thank my fellow archaeological geophysicists who provided images – as pictures are always ‘worth a thousand words’ their generosity strengthened the paper: Steve DeVore of the Midwest Archaeological Center, National Park Service; Aaron Fogel of Red Centre Consultancy; Edward Henry of the Center for Archaeological Research, University of Mississippi;

and, Duncan McKinnon of the University of Arkansas. In addition, I would like to thank Jessica Kowalski and Coastal Environments, Inc.; Dr Marie Danforth and the University of Southern Mississippi graduate students; Roger Hansen and Chevron’s Human Kind Program; Barbara Hester and the Mississippi Archaeological Association; the Mississippi Department of Archives and History; and the Jackson County Historical and Genealogical Society. Lastly, this review would not have been possible without a scholarship from The University of Queensland, who provided me with the opportunity to study archaeology in Australia.

References

Anschuetz, K. F., R. H. Scheick and C. L. Scheick 2001 An archaeology of landscapes: perspectives and direction. *Journal of Archaeological Research* 9(2):157–211.

Aspinall, A., C. Gaffney and L. B. Conyers 2008 Archaeological Prospection - the first fifteen years. *Archaeological Prospection* 15(4):241–245.

Aspinall, A., C. Gaffney and A. Schmidt 2008 *Magnetometry for Archaeologists.* Lanham, Maryland: AltaMira Press.

Astin, T., H. Eckardt and S. Hay 2007 Resistivity imaging survey of the Roman barrows at Bartlow, Cambridgeshire, UK. *Archaeological Prospection* 14(1):24–37.

Barrows, T. T., J. O. Stone, L. K. Fifield and R. G. Cresswell 2002 The timing of the last Glacial Maximum in Australia. *Quaternary Science Reviews* 21:159–173.

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

Bevan, B. W. 1998 *Geophysical Exploration for Archaeology: An Introduction to Geophysical Exploration*. Midwest Archaeological Centre Special Report No. 1. Lincoln: National Park Service, Midwest Archaeological Centre.

Bevan, B. W. 2006 Geophysical exploration for buried buildings. *Historical Archaeology* 40:27–50.

Bevan, B. W. and J. Kenyon 1975 Ground penetrating radar for historical archaeology. *MASCA Newsletter* 11(2):2–7.

Binford, L. R. 1968 Some comments on historical versus processual archaeology. *Southwestern Journal of Anthropology* 24:267–275.

Binford, L. R. 1987 Researching ambiguity: Frames of reference and site structure. In S. Kent (ed.), *Methods and Theory in Activity Area Research*, pp. 449–512. New York: Columbia University Press.

Bird, R. B., D. W. Bird, B. F. Codding, C. H. Parker and J. H. Jones 2008 The 'fire stick farming' hypothesis: Australian Aboriginal foraging strategies, biodiversity and anthropogenic fire mosics. *Proceedings of the National Academy of Sciences* 105:14796–14801.

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(4):249–257.

Bowler, J. M. 1973 Clay Dunes: Their occurrence, formation and environmental significance. *Earth-Science Reviews* 9:315–338.

Bowman, D. M. J. S. 1998 The impact of Aboriginal burning on the Australian biota. Tansley Review No. 101. *New Phytologist* 140:385–410.

Brooks, A., H. D. Bader, S. Lawerence and J. Lennon 2009 Ploughzone archaeology on an Australian historic site: A case study from south Gippsland, Victoria. *Australian Archaeology* 68:37–44.

Brown, S., S. Avery and M. Goulding 2002 Recent investigations at the Ebenezer Mission cemetery. In R. Harrison and C. Williamson (eds), *After Captain Cook: The Archaeology of the Recent Indigenous Past in Australia*, pp. 147–170. Lanham: Altamira.

Butzer, K. W. 1978 Cultural perspectives on geographical space. In K. W. Butzer (ed.), *Dimensions of Human Geography: Essays in Some familiar and Neglected Themes,* pp. 1–14. Research Paper 186. Chicago: Department of Geography, University of Chicago.

Caldwell, J. R. 1959 The new American archaeology. *Science* 129:303–307.

Campana, S. and S. Piro (eds) 2009 Seeing the Unseen: Geophysics and Landscape Archaeology. London: Taylor and Francis Group.

Casana, J., J. T. Herrmann and A. Fogel 2008 Deep subsurface geophysical prospection at Tell Qarqur, Syria. *Archaeological Prospection* 225:207–225.

Ciminale, M., D. Gallo, R. Lasaponara and N. Masini 2009 A multiscale approach for reconstructing archaeological landscapes: Applications in Northern Apulia (Italy). *Archaeological Prospection* 16:143–153.

Clark, A. 1996 *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Routledge.

Colley, S. 2000 Archaeology and education in Australia. *Antiquity* 74:171–177.

Compare, V., M. Cozzolino, P. Mauriello and D. Patella 2009 Three-dimensional resistivity probability tomography at the prehistoric site of Grotta Reali (Molise, Italy). *Archaeological Prospection* 63:53–63.

Connah, G., P. Emmerson and J. Stanley 1976 Is There a place for the proton magnetometer in Australian field archaeology? *Mankind* 10:151–155.

Conyers, L. B. 2004 *Ground-Penetrating Radar for Archaeologists*. Walnut Creek: AltaMira.

Conyers, L. B. and D. Goodman 1997 *Ground-Penetrating Radar: An Introduction for Archaeologists.* Walnut Creek: AltaMira.

Conyers, L. B., E. G. Ernenwein, M. Grealy and K. M. Lowe 2008 Electromagnetic conductivity mapping for site prediction in meandering river floodplains. *Archaeological Prospection* 15:81–91.

Conyers, L. B. and J. Leckebusch 2010 Geophysical archaeology research agendas for the future : Some ground-penetrating radar examples. *Archaeological Prospection* 123:117–123.

Conyers, L. B. 2011 Discovery, mapping and interpretation of buried cultural resources non-invasively with ground-penetrating radar. *Journal of Geophysics and Engineering* 8(3):S13–S22.

Cosgrove, D. E. 1984 *Social Formation and Symbolic Landscape*. London: Croom Helm.

Cushnahan, S. and M. Staniforth 1982 Magnetometers for Wrecksite Location. *The Bulletin of the Institute of Maritime Archaeology* 5:62–80.

Dalan, R. A. 2001 A magnetic susceptibility logger for archaeological application. *Geoarchaeology* 16(3):263–273.

Dalan, R. A. 2008 A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: Recent developments and prospects. *Archaeological Prospection* 15:1–31.

Dalan, R. A. and S. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13(1):3–36.

Dalan, R. A., G. R. Holley, W. I. Woods, H. W. Watters Jr and J. A. Koepke 2003 *Envisioning Cahokia : A Landscape Perspective*. DeKalb: Northern Illinois University Press.

Davenport, G. C. 2001 Remote sensing applications in forensic investigations. *Historical Archaeology* 35:87–100.

DeVore, S. L. 1998 Geophysical Investigations of the Western Part of Fort Casper Park, Natrona County, Wyoming. Unpublished report by the Midwest Archaeological Centre, National Park Service, Nebraska to the Intermountain Support Office, Denver.

Drahor, M. G., M. A. Berge, T. Ö. Kurtumlu, M. Hartmann and M. A. Speidel 2008 Magnetic and electrical resistivity tomography investigations in a Roman legionary camp site (Legio IV Scythica) in Zeugma, Southeastern. *Archaeological Prospection* 15:159–186.

Ernenwein, E. G. and K. L. Kvamme 2008 Data processing issues in large-area GPR surveys: Correcting trace misalignments, edge discontinuities and striping. *Archaeological Prospection* 15:133–149.

Fanning, P. C., S. J. Holdaway and R. S. Phillipps 2009 Heat-retainer hearth identification as a component of archaeological survey in western NSW, Australia. In A. Fairbairn, S. O'Connor and B. Marwick (eds), *New Directions in Archaeological Science*, pp. 13–23. Terra Australis 28. Canberra: ANU E-Press.

Fischer, P. M. 1980 *Applications of Technical Devices in Archaeology - The Use of X-rays, Microscope, Electrical and Electromagnetic Devices and Subsurface Interface Radar*. Studies in Mediterranean Archaeology LXIII. Goteborg: Paul Astroms Forlag.

Foley, R. 1981 Off-site archaeology. In I. Hodder, G. Isaac and N. Hammond (eds), *Patterns of the Past*, pp. 157–184. Cambridge: Cambridge University Press.

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

Gaffney, C. 2008 Detecting trends in the prediction of the buried past: A review of geophysical techniques in archaeology. *Archaeometry* 50(2):313–336.

Gaffney, C. and J. Gater 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing Ltd.

Gibbs, M. and D. Gojak 2009 Remote sensing in an urban Australian setting. *Australian Archaeology* 68:45–51.

Hall, J. and R. Yelf 1993 The application of ground penetrating radar in archaeology: A case from the Tower Mill, Brisbane. In B. L. Frankhauser and J. R. Bird (eds) *Archaeometry: Current Australasian Research*, pp. 121–130. Occasional Papers in Prehistory 22. Canberra: Department of Prehistory, Research of Pacific Studies, the Australian National University.

Herries, A. I. R. and E. C. Fisher 2010 Multidimensional GIS modelling of magnetic mineralogy as a proxy for fire use and spatial patterning: evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution* 59(3–4):306–20.

Hesse, P. P. and G. H. McTainsh 1999 Last Glacial Maximum to Early Holocene wind strength in the mid-latitudes of the Southern Hemisphere from aeolian dust in the Tasman Sea. *Quaternary Research* 52:343–349.

Hiscock, P. 2008 *Archaeology of Ancient Australia*. London: Routledge Taylor and Francis Group.

Hiscock, P. and L. A. Wallis 2005 Arid paradises or dangerous landscapes: A review of explanations for Paleolithic assemblage change in arid Australia and Africa. In P. Veth, M. Smith and P. Hiscock (eds), *Desert Peoples: Archaeolgoical Perspectives*, pp. 58–77. Oxford: Blackwell.

Jackson, J. B. 1995 In search of the proto-landscape. In G. F. Thompson (ed.), *Landscape in America*, pp. 43–50. Austin: University of Texas Press.

Johnson, J. K. (ed.) 2006 *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Tuscaloosa: University of Alabama.

Jones, R. 1969 Fire stick farming. *Australian Natural History* 16:224–228.

Jones, R., A. Challands, C. French, N. Card, J. Downes and C. Richards 2010 Exploring the location and function of a Late Neolithic house at Crossiecrown, Orkney by geophysical, geochemical and soil micromorphological methods. *Archaeological Prospection* 17:29–47.

Jordan, D. 2009 How effective is geophysical survey ? A regional review. *Archaeological Prospection* 16:77–90.

Keay, S., G. Early, S. Hay, S. Kay, J. Ogden and K. D. Strutt 2009 The role of integrated geophysical survey methods in the assessment of archaeological landscapes: The case of Portus. *Archaeological Prospection* 16:154–166.

Keys, B. O. 2009 *Engrained in the Past: Using Geoarchaeology to Understand Site Formation Processes at the Gledswood Shelter 1 Site, Northwest Queensland.* Unpublished BArch (Honours) thesis, Department of Archaeology, Flinders University, Adelaide.

Kvamme, K. L. 2001 Current Practices in Archaeogeophysics. In P. Goldberg, V. T. Holliday and C. R. Ferring (eds), *Earth Science and Archaeology*, pp. 353–382. New York: Klumer Academic/Plenum Publisher.

Kvamme, K. L. 2003 Geophysical surveys as landscape archaeology. *American Antiquity* 68(3):435–457.

Kvamme, K. L. 2006 Magnetometry: Nature's Gift to Archaeology. In J.K. Johnson (ed.), *Remote Sensing in Archaeology: An Explicitly North American Perspective,* pp. 205–253. Tuscaloosa: University of Alabama Press.

Lawrence, D. and S. M. Low 1990 The built environment and spatial form. *Annual Review of Anthropology* 19:453–505.

Lindsay, I., A. T. Smith and R. Badalyan 2010 Magnetic survey in the investigation of sociopolitical change at a Late Bronze age fortress settlement in northwestern Armenia. *Archaeological Prospection* 17(1):15–27.

Long, A. and T. von Strokirch 2003 *Lost But Not Forgotten: A Guide to methods of Identifying Aboriginal Unmarked Graves*. Sydney: New South Wales National Parks and Wildlife Service.

Lowe, K. M. 2011 Ground-Penetrating Radar Survey on Historic Krebs Cemetery: Search for Unmarked Burials, Pascagoula, Mississippi. Unpublished report to Jackson County Historical and Genealogy Society, Pascagoula.

Lowe, K. M. and A. S. Fogel 2010 Understanding Northeastern Plains Village sites through archaeological geophysics. *Archaeological Prospection* 17:247–257.

Marwick, B. 2005 Element concentrations and magnetic susceptibility of anthrosols: Indicators of prehistoric human occupation in the inland Pilbara, Western Australia. *Journal of Archaeological Science* 32:1357–1368.

McDougall, M., D. Massie and J. P. Cull 1997 Ground Penetrating Radar Investigation, Former Ebenezer Mission Cemetery. Unpublished report to Aboriginal Affairs Victoria, Melbourne.

McNeill, J. D. 1980 *Electrical Conductivity of Soils and Rocks.* Technical Note TN-5. Ontario: Geonics.

Meggers, B. J. 1979 *Prehistoric America: An Ecological Perspective*. New York: Aldine Publishing Company.

Milani, J. L. 2010 *Unveiling Rock Art Images: A Pilot Project Employing a Geophysical Technique to Detect Magnetic Signatures*. Unpublished MArch Thesis, Department of Archaeology, Flinders University, Adelaide.

Moffat, I., L. A. Wallis, A. Beale and D. Kynuna 2008 Trialing geophysical techniques in the identification of open Indigenous sites in Australia: A case study from inland Northwest Queensland. *Australian Archaeology* (66):60–63.

Moffat, I., L. A. Wallis, M. W. Hounslow, K. Niland, K. Domett and G. Trevorrow 2010 Geophysical prospection for late Holocene burials in coastal environments: Possibilities and problems from a pilot study in South Australia. *Geoarchaeology* 25(5):645–665.

Mooney, S, C. Geiss and M. A. Smith 2003 The use of mineral magnetic parameters to characterize archaeological ochres. *Journal of Archaeological Science* 30:511–523.

Mulvaney, D. J. 1975 *The Prehistory of Australia*. Penguin: Melbourne.

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

Novo, A., H. Lorenzo, F. I. Rial and M. Solla 2010 Three-dimensional ground-penetrating radar strategies over an indoor archaeological site: Convent of Santo Domingo (Lugo, Spain). *Archaeological Prospection* 17:213–222.

Olhoeft, G. R. 1981 Electrical properties of rocks. In Y. S. Touloukian, W. R. Judd and R. F. Roy (eds), *Physical Properties of Rocks and Minerals*, pp. 257–330. New York: McGraw-Hill.

Ortega, A. I., A. Benito-Calvo, J. Porres, A. Pérez-González and M. A. Martín Merino 2010 Applying electrical resistivity tomography to the identification of endokarstic geometries in the Pleistocene sites of the Sierra de Atapuerca (Burgos, Spain). *Archaeological Prospection* 17:233–245.

Papadopoulos, N. G., G. N. Tsokas, M. Debas, M. Yi, J. Kim and P. Tsourlos 2009 Three-dimensional inversion of automatic resistivity profiling data. *Archaeological Prospection* 16:267–278.

Pearson, M. and S. Sullivan 1999 *Looking After Heritage Places: The basics of Heritage Planning for Managers, Landowners and Administrators*. Melbourne: Melbourne University Press.

Petronille, M., J. Thiesson, F. X. Simon and O. Buschsenschutz 2010 Magnetic signal prospecting using multiparameter measurements: The case study of the Gallic site of Levroux. *Archaeological Prospection* 17:141–150.

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

Powell, K. 2010 *Grave Concerns: Locating and Unearthing Human Bodies*. Bowen Hills: Australian Academic Press.

Preucel, R. W. and I. Hodder (eds) 1996 *Contemporary Archaeology in Theory: A Reader*. Oxford: Blackwell Publishing.

Randolph, P., V. Wilson, C. Frampton and G. Merritt 1994 Rottnest Island Aboriginal Prisoners Cemetery: Delineation of extent using ground-penetrating radar. In M. Sullivan, S. Brockwell and A. Webb (eds), *Archaeology in the North: Proceedings of the 1993 Australian Archaeological Association Conference*, pp. 394–415. Darwin: North Australia Research Unit, Australian National University.

Ranson, D. and B. Egloff 1988 The Application of earth-resistivity surveys to Australian archaeological sites. *Australian Historical Archaeology* 6:57–73.

Reynolds, J. M. 1997 *An Introduction to Applied and Environmental Geophysics*. Chichester: John Wiley and Sons.

Roberts, B. K. 1987 Landscape archaeology. In J.M. Wagstaff (ed.), *Landscape and Culture-Geographical and Archaeological Perspectives*, pp. 77–95. Oxford: Basil Blackwell.

Rossignol, J. 1992 Concepts, methods and theory building: A landscape approach. In J. Rossignol and L. Wandsnider (eds), *Space, Time, and Archaeological Landscapes*, pp. 3–16. New York: Plenum Press.

Rossignol, J. and L. Wandsnider (eds) 1992 *Space, Time and Archaeological Landscapes*. New York: Plenum Press.

Scollar, I. 1971 A magnetometer survey of the Colonia Ulpin Trajana near Xantern, west Germany. Prospezioni *Archeologiche* 6:83–92.

Simpson, D., M. van Meirvenne, T. Saey, H. Vermeersch, J. Bourgeois, A. Lehouck, L. Cockx and U. W. A. Vitharana 2009 Evaluating the multiple coil configurations of the EM38DD and

DUALEM-21S sensors to detect archaeological anomalies. *Archaeological Prospection* 16:91–102.

Smith, C. and H. Burke 2007 *Digging It Up Down Under: A Practical Guide to Doing Archaeology in Australia*. New York: Springer Science.

Somers, L. 2006 Resistivity surveys. In J. K. Johnson (ed.), *Remote Sensing in Archaeology: An Explicitly North American Perspective,* pp. 109–129. Tuscaloosa: University of Alabama Press.

Stanger, R. and D. Roe 2007 Geophysical surveys at the West End cemetery, Townsville: An application of three techniques. *Australian Archaeology* 65:44–50.

Stanley, J. M. 1983 Subsurface survey: the use of magnetics in Australian archaeology. In G. Connah (ed.), *Australian Field Archaeology: A Guide to Techniques,* pp. 82–86. Canberra: Australian Institute of Aboriginal Studies.

Stanley, J. M. and G. Connah 1977 Magnetic evidence of an Aboriginal burial ground at Forster, NSW. In P. Coutts and R. Brooks (eds), *A Collection of Papers Presented to ANZAAS 1977 (Vol. 2),* pp. 37–50. Melbourne: Memoirs of the Victorian Archaeological Survey.

Stanley, J. M. and R. Green 1976 Ultra-rapid magnetic surveying in archaeology. *Journal of Applied Geophysics* 14:51–56.

Stanley, J. M. 1975 Applications of a rapid sampling vehicle borne magnetometer. *Australia Society Exploration Geophysics Bulletin* 6:100–103.

Stilgoe, J. R. 1982 *Common Landscapes of America, 1580-1845*. New York: Yale University Press.

Stringfield, M. S., S. Hamilton, J. Liebans, J. K. Johnson, B. S. Haley, A. Fogel, K. Kennedty and S. Williams 2008 The search for the hidden people of St. Michael's cemetery: Pensacola, Florida. Report of Investigation #158. Pensacola: Archaeological Institute, University of West Florida.

Sutton, M.-J. and L. B. Conyers 2013 Understanding cultural history using ground-penetrating radar mapping of unmarked graves in the Mapoon Mission Cemetery, Western Cape York, Queensland, Australia. *International Journal of Historical Archaeology* 17(4):782–805.

Thompson, R. and F. Oldfield 1986 *Environmental Magnetism*. London: Allen and Unwin.

Tite, M. S. 1972 *Methods of Physical Examination in Archaeology*. London: Seminar Press.

von Strokirch, T. 1999 A report on a ground magnetic Survey over the Ebenezer Mission cemetery and Surrounds. Unpublished report to Aboriginal Affairs Victoria, Melbourne.

Wagner, P. L. 1972 *Environments and Peoples*. Englewood Cliffs: Prentice-Hall.

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

Wallis, L. A., H. Smith and D. Smith 2004 Investigations of Aboriginal hearth sites along the Flinders River, inland northwest Queensland. *The Artefact* 27:59–76.

Webb, S. 2007 Further research of the Willandra Lakes fossil footprint site, southeastern Australia. *Journal of Human Evolution* 52(6):711–715.

West, G. E. and J. C. Macnae 1991 Physics of the electromagnetic induction exploration method. In M. N. Nabighian and E. B. Neitzel (eds), *Electromagnetic Methods in Applied Geophysics*, pp. 5-45. Tulsa: Society of Exploration Geophysics.

Weymouth, J. W. 1979 Technical developments and results of the 1977 season of the Great Plains magnetic surveying program. *Archaeo-Physica* 10:710–717.

Weymouth, J. W. 1986 Geophysical methods of archaeological site surveying. *Advances in Archaeological Method and Theory* 9:311–395.

Wilkinson, K. and C. Stevens 2003 *Environmental Archaeology: Approaches, Techniques and Applications*. Gloucestershire: Tempus Publishing.

Willey, G. R. and P. Phillips 1955 Method and theory in American archaeology II: Historical-developmental interpretation. *American Antiquity* 57:723–819.

Witten, A. J. 2006 *Handbook of Geophyics and Archaeology*. London: Equinox Publishing.

Yelf, R. and A. Burnett 1995 Ground-Penetrating Radar Survey of Unmarked Cemeteries at Taroom Aboriginal Reserve, Bundulla, Queensland. Unpublished report to the Department of Environment and Heritage, Rockhampton.

Yibarbuk, D., P. J. Whitehead, J. Russell-Smith, D. Jackson, C. Godjuwa, A. Fisher, P. Cooke, D. Choquenot and D. M. J. S. Bowman 2001 Fire ecology and Aboriginal land management in central Arnhem Land, northern Australia: A tradition of ecosystem management. *Journal of Biogeography* 28(3):325–343.

CHAPTER 3

USING SOIL MAGNETIC PROPERTIES TO DETERMINE THE LEVEL OF ONSET OF HUMAN OCCUPATION AT AUSTRALIAN ARCHAEOLOGICAL SITES

Chapter 3 is reproduced from the article submitted to *Geoarchaeology* and is part of the thesis question regarding onset of human settlement. It has been reformatted for this thesis chapter.

Lowe, K. M., J. Shulmeister, J. A. Feinberg, T. Manne, L. A. Wallis and K. Welsh Using soil magnetic properties to determine the level of onset of human settlement at Australian archaeological sites. Submitted to Geoarchaeology in January 2014, revised and resubmitted in May 2014.

3.1 Abstract

In regions that lack built structures or stratified open archaeological sites, such as pre-colonial Australia, rockshelters are a major source of detailed information for understanding the nature and timing of human occupation. Here, we present evidence of magnetic changes occurring with the onset of human occupation as determined from the appearance of stone artefacts in a Pleistocene-aged rockshelter in interior northern Queensland. Sediment magnetic susceptibility studies combined with experimental burning show that magnetically enhanced sediments in the rockshelter are the result of anthropogenic burning and not caused by natural fires, pedogenesis or weathering. These techniques appear to work in this setting because of the nature of the local geology and the geological antiquity of the landscape, and overcome traditional problems interpreting magnetic signals from Australian landscapes caused by frequent natural wildfires. The susceptibility and frequency dependence signatures provide a critical tool to resolve where in a stratigraphic section human occupation starts and finishes. In association with luminescence dating, it will allow archaeologists to resolve issues around the timing of human settlement in Australia and other cratonic plate settings such as southern Africa.

3.2 Introduction

There is ongoing debate regarding both the timing of the earliest human arrivals in Australia, and the nature of their subsequent colonisation of the continent. Most researchers now accept that Australia was first occupied at least 45,000 to 50,000 years ago, based on radiocarbon age determinations, while claims of older occupation beyond 60,000 years, (Thorne et al. 1999) and even 130,000 years have been proposed, (Kershaw et al. 1993) but are not widely accepted (O’Connell and Allen 2004; Forster et al. 2001). A key concern for many is that the ages proposed for the earliest archaeological sites are based on luminescence dating of sediments, rather than directly of cultural materials; as such, the association between the sediments and the evidence of human activity is questionable.

The stratigraphic assessment of sediment magnetic susceptibility allows the detection of magnetic minerals in sediments, the presence of which can be due to both cultural and natural processes (i.e. fires, pedogenesis or chemical weathering) (Dalan and Banerjee 1998; Ellwood et al. 1997; Herries and Fisher 2010; Linford et al. 2005). In Australia, the archaeological applications of mineral magnetics have been very limited owing to both the high iron content in the landscape and the widespread modification of magnetic signals by natural fires (Lowe 2012). In this paper we present a case study from northern Australia that allow us to use these signals to decipher the history of human occupation in a rockshelter and, in so doing, allow critical questions of site integrity and anthropogenic-sediment associations to be addressed.

Geologically, northern Australia comprises an old continental craton of granitic rocks, overlain by Proterozoic to Mesozoic quartz-rich sandstones that are only weakly magnetic (Stevens 1972). Globally, fire (either anthropogenic or natural) is the primary mechanism for causing magnetic enhancement of sediments and increases in magnetic susceptibility, though pedogenesis and chemical weathering can also cause similar effects (Le Borgne 1955; Longworth and Tite 1977; Tite and Mullins 1971). Magnetic susceptibility is a measure of a sample’s ability to be magnetised in a low-intensity field and is characterised by the concentration or mass fraction of the dominant carrier, mineralogy and magnetic grain size (Thompson and Oldfield 1986). When burned, changes to sediment mineralogy affecting magnetic susceptibility occur and these are related to the temperature and duration of the burn, organic content of the sediments and the type and relative abundance of iron-bearing minerals (Bellomo 1993; Linford and Canti 2001; McClean and Kean 1993).

One magnetic parameter that receives some attention worldwide but has been rarely utilised in Australian archaeology is the frequency dependence of susceptibility (χfd). Frequency dependence is the difference between the measured magnetic susceptibilities of a sediment at low and high frequency, and is expressed either as a relative loss of susceptibility (χfd = (χ460Hz-χ4600Hz), or a percentage loss of the low frequency value (χfd% = (χ460Hz-χ4600Hz/χ460Hz*100) (Dearing et al. 1996; Maher 1986). Measurement of χfd% shows in practice the contribution of ultrafine magnetic grains (>0.03 µm) (known as 'superparamagnetic' grains, hereafter SP) (Dearing et al. 1999). An increase in χfd with an increase in magnetic susceptibility potentially suggests an increase in the percentage of SP grains or those grains near the SP-single domain (SD) boundary (>0.03 µm to ca 0.2-110 µm) (Dearing et al. 1999).

Our case study is a Pleistocene-aged sandstone rockshelter, Gledswood Shelter 1 (GS1) located in monsoonal northern Australia (Figure 3.1). At this site, there is a clear archaeological level at which stone artefacts appear and this level can be easily distinguished from the culturally sterile levels below. This onset of artefacts had initially been dated to about 28,000 years ago using radiocarbon (Wallis et al., 2009), but recalibration of the dates in addition to more dated samples have pushed the site back to about 38,000 years ago (Wallis et al., unpublished data). For this study the age of settlement is less important than our clear ability to distinguish the stratigraphic depth of onset of human occupation.

The GS1 shelter is 8 m high and 7 m wide, with overhanging sandstone providing a protected area of 3 m². The shelter floor is sandy and mostly vegetation free, with the exception of sparse grasses and occasional low herbs. Within the overhang, six adjoining 1 x 1 m test-pits (Squares B0, B1, C0, C1, D0 and D1) were excavated in arbitrary ~5 cm layers (spits or excavation units) to bedrock, which was reached at a maximum depth of ca 2.6 m (Figure 3.1). These test-pits were described using standard stratigraphic and archaeological techniques and with the aid of a Munsell colour chart (Wallis et al. 2009). The sequence was dated using radiocarbon ages on charcoal. Seven stratigraphic units (SU) have been defined based on textural and sediment morphological characteristics. Sediments within the shelter consisted of fine to medium sands with sesquioxide coatings, giving the sands a reddish yellow (7.5YR 6/6) to pink (7.5YR 8/4) colour near the basal layers which trend to a light yellowish brown (10YR6/4) to dark greyish brown (10YR 4/2) near the surface. Four 50 x 50 cm area test pits (TP01-04) beyond the overhang (i.e. 'off-site') were excavated to 1.2 m depth for the purposes of providing ‘natural’ control sites to compare to the overhang sediments and understand the local environment. These sediments also consisted of light yellowish brown (10YR 6/4) to dark grayish brown (10YR 4/2), fine to medium sands with sesquioxide coatings.

Stone artefacts were recovered to approximately 2.2 m depth (the precise depth varied between test pits), below this level there is no evidence of human use of the site. Other artefactual material like ochre and wood charcoal was also observed (Carah 2010). Bone and organics were minimal due to poor preservations conditions.

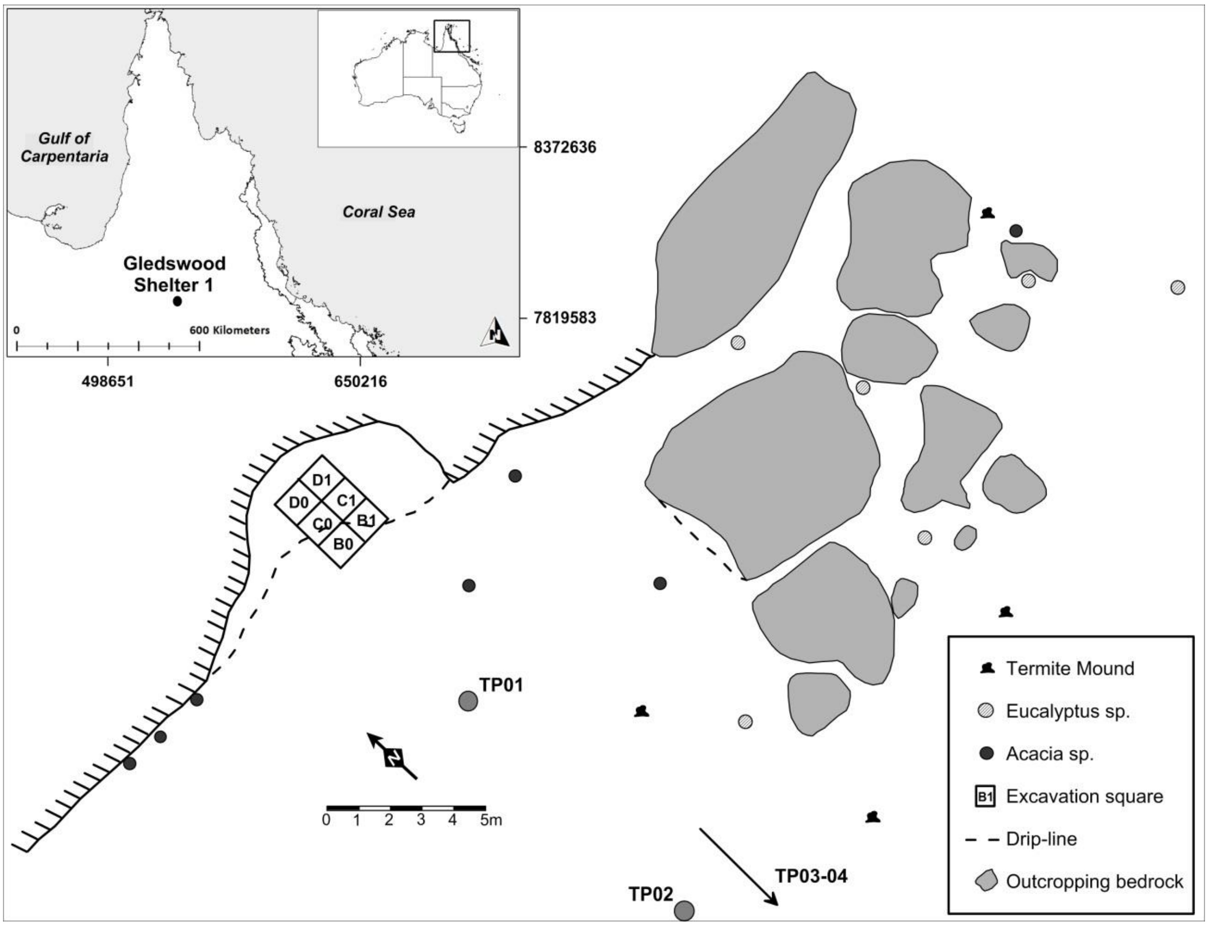

Figure 3.1 Map showing location of project area and local site setting (modified from Wallis et al. 2009:Figure 1; Geoscience Australia 2004).

3.3 Methods

Sedimentary analysis included sedimentological description, magnetic susceptibility, loss on ignition (LOI), available phosphorus (P) and wood charcoal (see Carah 2010 for more detail on species). Correlations between the datasets were then assessed to help distinguish sediment magnetic inputs and to determine when people first began visiting the site.

Sediment magnetic analyses were measured in the lab with the Bartington Instruments MS2B sensor. Samples were taken every 5 cm layer in the GS1 test-pits, and every 20 cm in the off-site test-pits and were packed in small non-magnetic Althor P15 boxes (5.28 cc volume). Both low-field mass and volume magnetic susceptibility readings (χ and K) at a 0.1 range were taken using both low and high frequency (460 and 4600 Hz) for χfd%. These were followed with anhysteretic remanent magnetisation (ARM), saturation isothermal remanent magnetisation (SIRM), hysteresis loops, and high (Curie point) and low temperature analyses at the Institute of Rock Magnetism at the University of Minnesota.

The ARM, SIRM, hysteresis loops and high and low temperature tests were measured on selected samples from Squares C1, B1 and D1 to investigate the mineralogy, concentration and grain size. ARM was imparted with a peak field of 200 mT, and a steady field of 0.1 mT using an Alternating-field demagnetiser. Measurements were followed on a 2G Superconducting Rock Magnetometer. Samples were then saturated in a field of 1 T using a pulse magnetiser and the produced SIRM was measured on the 2G Superconducting Rock Magnetometer. Hysteresis loops were carried out to investigate saturation magnetisation (Ms), saturation remanent magnetisation (Mr), coercivity (Hc), coercivity of remanance (Hcr) and the ferromagnetic portion of the susceptibility signal to saturation magnetisation (χferri). Hysteresis loops were conducted on a Princeton Measurement MicroMag Vibrating Sample Magnetometer using a maximum field of 1 T, a time constant 0.01 seconds and steady field increments to about 200 mT and then to 1 T for highly magnetised samples.

High (Curie point) and low temperature analyses of the sediments were then undertaken on selected samples (n = 15) within the shelter, mainly those exhibiting magnetic enhancement within each SU; however, a few weakly magnetic samples were also selected (n = 4), with two chosen from the culturally sterile basal units. For high temperature investigations, each sample was heated up to 600–650°C to determine the Curie point, which allows the identification of the specific magnetic minerals (Banerjee 1981; King et al. 1982; Thompson and Oldfield 1986). High temperature investigations were conducted on a Geofyzika KLY-2 KappaBridge AC Susceptibility Bridge.

Low temperature measurements involved the examination of magnetic remanence of the samples as they were warmed and cooled using the Quantum Designs MPMS-52 (magnetic properties measurement system). An initial field of 2.5 T was imparted before samples were measured. Samples where then cooled from room temperature (300K) to 20 K and the remanence was measured at 5 K increments in a zero field. The samples were given another remanence of 2.5 T at 20 K, and warmed from 20 K up to 300 K, measuring remanence in a zero field at 5 K increments. Low temperature susceptibility measurements at 4 frequencies (1, 5.6, 31.6 997.3 Hz) were also carried out using temperatures from 20 to 300 K.

Controlled burning experiments in a muffle furnace were used to examine the effect of different burning regimes on the magnetic response of these samples. It is noted that these will not replicate the exact heating conditions in a fireplace, the overall goal was to see if mineralogical transformations occurred. Published burning experiments have shown that samples exposed to temperatures of >300°C are generally sensitive to magnetic modifications (Carrancho and Villalaín 2011; Lindford and Canti 2001; Morinaga et al. 1999). Controlled temperatures between 400°C and 800°C were used because this range represents those conditions that are typical of hearth temperatures (Linford and Canti 2001; McLean and Kean 1993). These experiments were focused on the 'natural' sediments from the off-site test pits. A total of 20 samples were used, five from each of the four test pits. Two sets of tests were completed. Both involved heating the samples to the maximum temperature and maintaining that temperature for 1 hour. This replicates a typical cooking fire situation, where maximum temperatures are not normally maintained for an extended period (Singh et al. 1990; McLean and Kean 1993). The samples were then air-cooled. In the first test the sediment was heated alone. In the second test a wood fuel source was added to the sediment sample. The wood fuel was varied between the common types of wood available at the GS1 site, i.e. *Eucalyptus* and *Acacia* spp. and *Ficus* wood was used as a control. The differences in susceptibility for both χ and K and χfd values were then measured.

3.3.1 Other Parameters

Excavated materials recovered from the site were dry-sieved through 3 and 7 mm sieves. The 7 mm fraction was sorted in the field, the remaining 3 mm fraction was sorted in the laboratory. Stone artefacts and ochre recovered from each spit were analysed noting raw material type, length, width and height. Other material collected included wood charcoal. It was collected from both the 7 and 3 mm fractions, weighed and volumetrically corrected. A 10 g subsample of bulk sediment from each level was ashed for ~12 hours in a muffle furnace at 450ºC to measure LOI. The temperature was kept this low to prevent combustion of carbonates. Subsamples for available P analysis were also taken from each level, air-dried and sieved through a 2 mm mesh. Phosphorus extraction was done using a Mehlich 3 technique (after Rayment and Lyons 2011:398–402) which is used for sediments high in iron and/or aluminum. P was measured using a Varian Vista Port ICPOES (inductively coupled plasma optical emission spectrometry) instrument.

3.4 Results

The magnetic susceptibility data reveals a strong correlation between the SU's within the GS1 sedimentary sequence (Figure 3.2). As shown, the GS1 samples are weakly magnetic in the culturally sterile layers (the basal units of lower SU6, SU7 and SU8) and are similar in magnitude to those from the off-site control samples outside the overhang. The χfd% measurements in these lower basal units are on average about 16%, with erroneous values in the lower deposits due to noise. Susceptibility values rise rapidly at the point in the sequence where artefacts first occur and remain consistently higher than those recorded in the basal units. There is also a positive correlation between susceptibility and other parameters like wood charcoal, LOI and P. Susceptibility values are highest in the upper portion of the sequence or in SU1, SU2 and SU3. Measurements from the off-site control test-pit sediments show minimal enhancement of magnetic susceptibility and χfd% (3–6%), while almost all samples within the shelter have a higher χfd% (9–12%), indicating they contain a greater percentage of SP grains.

Bivariate plots were used to discern relative magnetic changes between the stratigraphic units and the squares. Plots of ARM against χ were used to understand the magnetic mineral concentrations and grain sizes. Although both depend on magnetic concentrations, ARM is more sensitive to SD particles, while χ is more sensitive to larger pseudo-single domain (PSD) and multidomain (MD) magnetic grains (King et al. 1982). The slope change of a line fitted to the plotted samples were evaluated to understand variations in relative grain size, while the distribution of points with respect to the line's origin represent an increase in concentration of the ferromagnetic material. The ARM versus χ plot of samples from Square C1 indicates an increase in the concentration of the magnetic carrier in the upper stratigraphic units (SU1, SU2 and SU3) (Figure 3.3a) (see supplementary data for Squares C0 and D1). All samples generally plot along the same line, indicating a similar-sized magnetic material. However, samples in SU7 and SU8 may be slightly finer grained. This is confirmed in the ARM versus SIRM plot, which is also used to look at dominate grain sizes and magnetic mineral concentrations (Figure 3.3b).

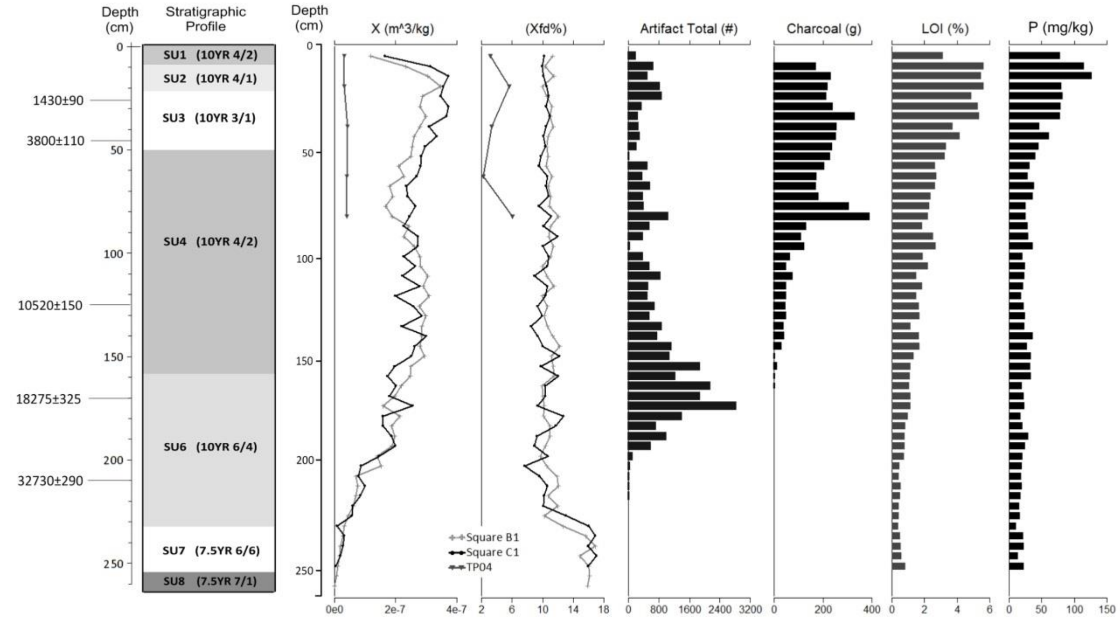

Figure 3.2 **Profile of low-field magnetic susceptibility and frequency dependence for Squares B1 and C1, and Test Pit 04. Stratigraphic profile, stone artefacts, wood charcoal, loss on ignition and phosphorus data are also provided, SU5 is not defined therefore omitted from profile. Laboratory numbers for radiocarbon dates from top to bottom: ANU-2625, Wk-33293, Wk-33294, Wk-33295, OZM094. Note higher magnetic signatures within the shelter and change with onset of human occupation. Samples are weakly magnetic in the cultural sterile layers.**

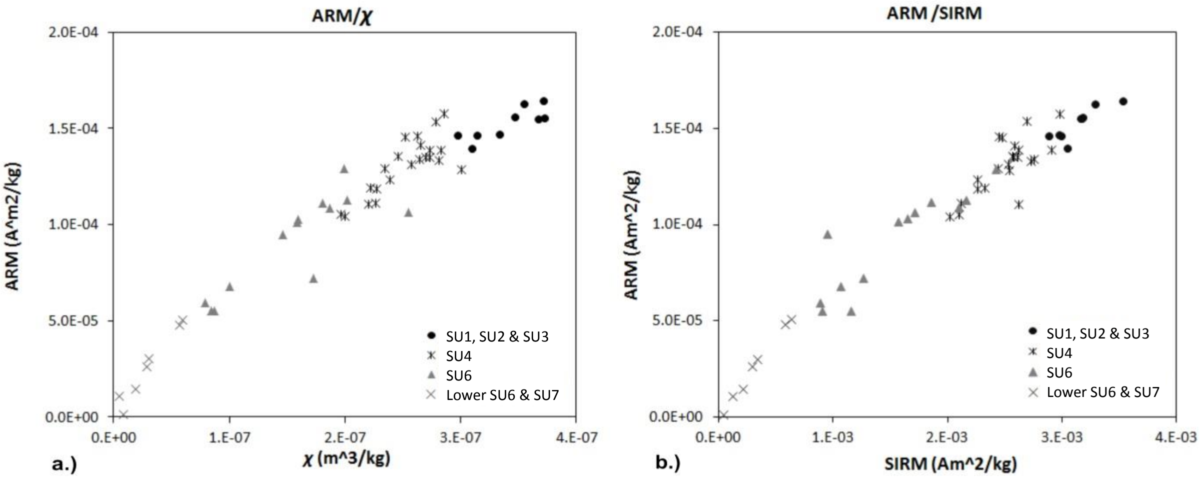

Figure 3.3 **Plots of (a) ARM susceptibility versus mass susceptibility and (b) ARM susceptibility versus SIRM susceptibility for Square C1 samples.**

The hysteresis measurements demonstrate that both Ms and Mr, and Hc and Hcr increase with decreasing depth (Figure 3.4). The Mr/Ms and Hcr/Hc ratios also have a general trend of increasing with decreasing depth (see Figure 4). This indicates that Hcr increases at a faster rate than Hc with depth. Bivariate plots of Mr/Ms versus Hc show that the samples fall squarely between the reference line between pure magnetite and titanomagnetite (TM) 60 (see supplementary data).

These variations demonstrate that there is less ferromagnetic material with depth in the GS1 sediments and an increase in the relative abundance of magnetically hard minerals such as hematite and goethite (Jackson et al. 1990). This occurs between the lower portion of SU4 and upper portion of SU6, around 140–150 cm and suggests that the sediment input is less external in these units. The χferri/Ms ratio which is also related to variations in the content of SP particles of magnetite and maghemite was used to corroborate the trends in the χfd data (Dalan 2006). This ratio was slightly larger in the lower portion of the stratigraphic sequence (mid-SU4 and upper SU6) than in the upper portion. The ratio ARM/SIRM was also used to understand trends in the data (Evans and Heller 2003). This ratio was more variable and only slightly larger for those deposits found in the lower portion of the sequence.

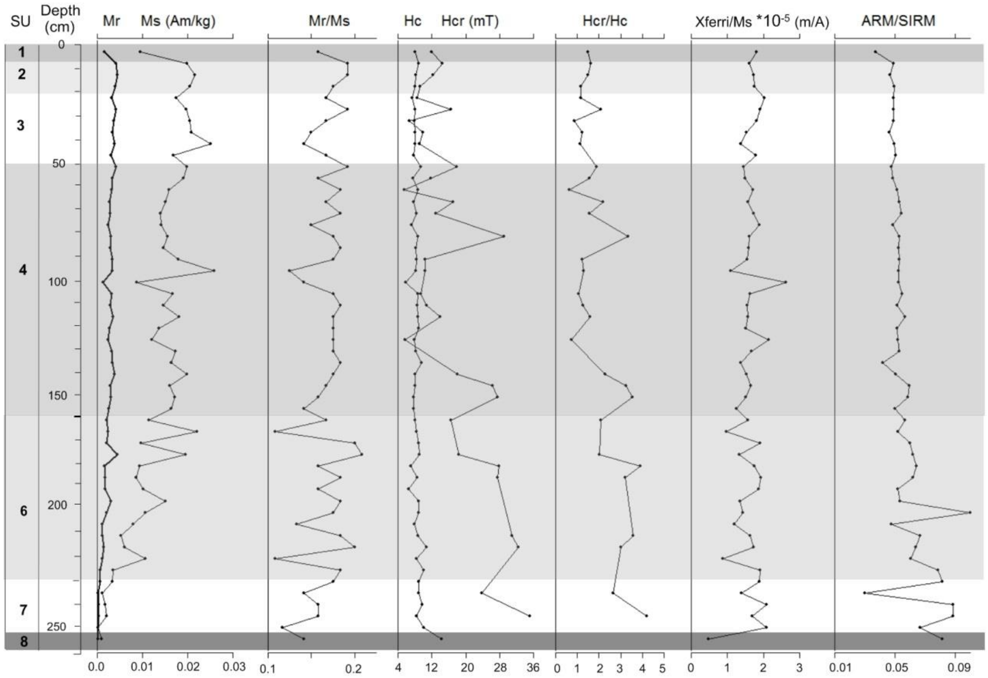

Figure 3.4 Selected sediment magnetic parameters for Square C1.

Curie point temperatures on measured samples ranged from 537 to 594°C. Almost all samples have Curie points <580°C and so are not pure magnetite, but likely represent magnetite with impurities such as titanium, aluminium or magnesium, which are known to depress the Curie point temperature (Thompson and Oldfield 1986). Temperature curves, which are useful in evaluating the thermal stability of minerals reveal both thermally unstable (irreversible susceptibility curves on cooling) and thermally stable (reversible susceptibility curves on cooling) minerals. Irreversible susceptibility curves were found in SU1, SU2, SU3 and the upper portion of SU4 (Figure 3.5a). Susceptibility curves that were reversible were found in the lower portion of SU4 and the upper portion of SU6 (Figure 3.5b-c); only minor amounts of additional susceptibility was created at the end of the experiments. Samples that were extremely irreversible were found in SU7 (Figure 3.5d). No high temperature tests were run for SU8 due to the very low levels of χ.

The presence of two ferrimagnetic phases and irreversible curves in the upper units indicate mineralogical transformations; firstly the inversion of a magnetic mineral that begins around 300°C and secondly, the formation of new magnetic phase such as maghemite. Mineralogical transformations such as these are likely related to the presence of carbon (e.g. charcoal) or other carbon-rich organic material. When this material is added to soil and heated, common Fe-bearing soil minerals like goethite, ferrihydrite and hematite can be transformed to more strongly magnetic phases like magnetite and maghemite (Hanesch et al. 2006). This transformation starts below 400°C for ferrihydrite and lepidocrocite and around 450°C for goethite. Both charcoal and LOI are also higher in those upper units (SU1, SU2, SU3 and the upper portion of SU4). Alternatively, SU6 has lower concentrations of carbon-rich material and thus no mineral transformations. Low levels of carbon also exist in SU7; however, the extremely low values of χ produced a dramatic amount of new magnetic material during the heating experiments suggesting that this stratigraphic unit may contain detrital titanomagnetite.

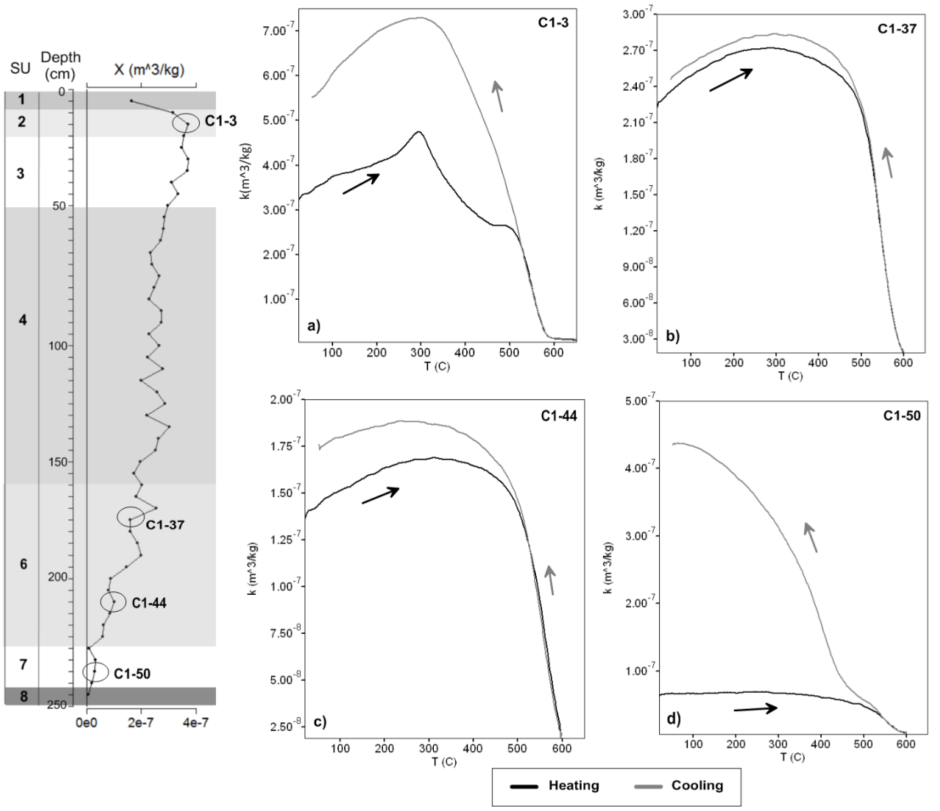

Figure 3.5 **High temperature (Curie point) curves on selected samples of (a) irreversible curves and the inversion of a new magnetic mineral, (b-c) reversible curves with only a minor amount of susceptibility created and (d) extremely irreversible curves and the inversion of a large amount of magnetic material.**

Low temperature measurements indicated some similarities and differences between the stratigraphic units. The Verwey transition is observed on the cooling leg for all samples under 115 K (Figure a-d). This transition is also observed on the warming leg for all samples, indicating that the magnetite is present but not oxidised. Fine-grained enhancement of magnetite mixed with goethite and hematite were present in all the GS1 sediment samples selected for analysis. While these are common soil forming minerals, their relative concentration within each component differs in each sample indicating that they are not natural environmental processes.

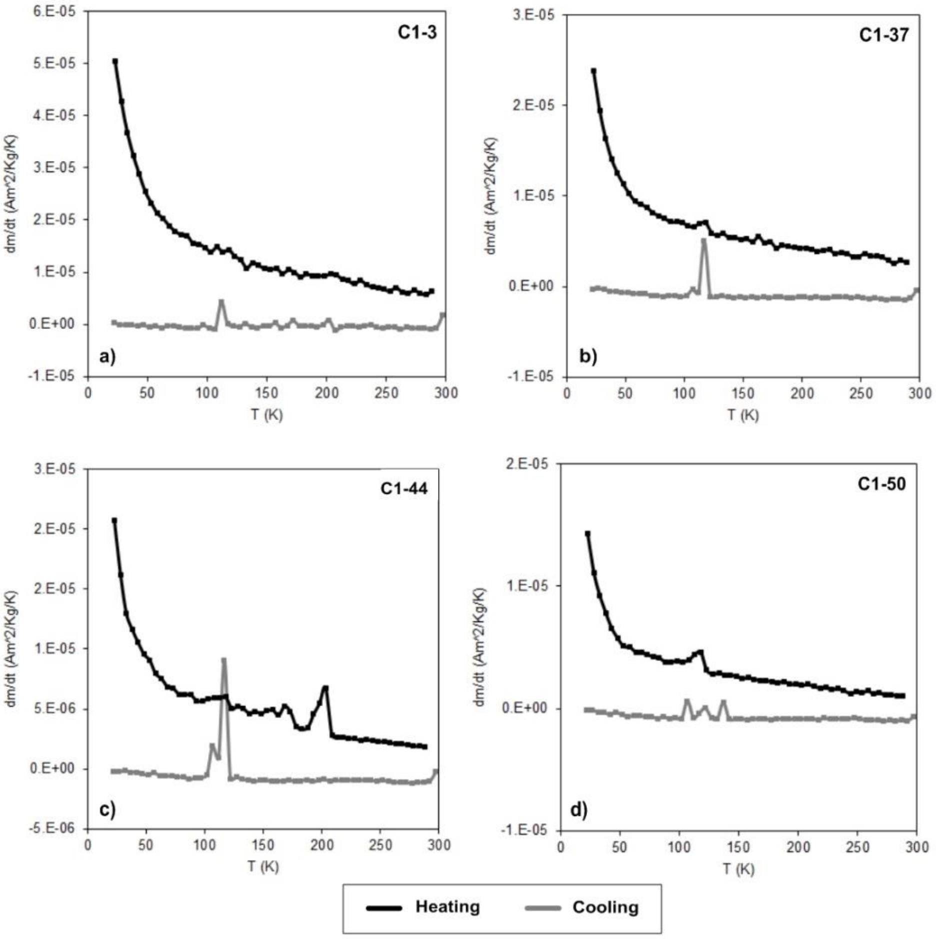

Figure 3.6 **Low temperature derivative plots on selected samples confirm the presence of magnetite (refer to Figure 3.5 for sample location). All samples show evidence of magnetite and goethite. Samples (a) also reveals evidence of hematite and a hint of an inflection ~70 K that is consistent with ilmenite, (b) only shows magnetite and goethite, (c) also contains evidence of nano-hematite while (d) contains hematite.**

The burning experiments indicated that wood ash contributes significantly to increases in both magnetic susceptibility and χfd% (Figure 3.7). Experiments where wood fuel was not added to the sample showed limited changes in susceptibility values, with changes restricted to colour only. In some cases where multiple experiments on the same sample were completed, the susceptibility actually decreased, supporting observations (Maki et al. 2006) that high temperatures of ferrimagnetic grains occurred, forming hematite. When a fuel source was added to the sediment samples and burned, susceptibility increased by up to three magnitudes, as did the χfd% indicating that thermal alterations between the sediment minerals and wood fuel occurs (McClean and Kean 1993). The burning of *Acacia* and *Eucalyptus* spp. fuels (the dominant tree genera across much of Australia) was more effective for raising susceptibility and χfd values than the Ficus.

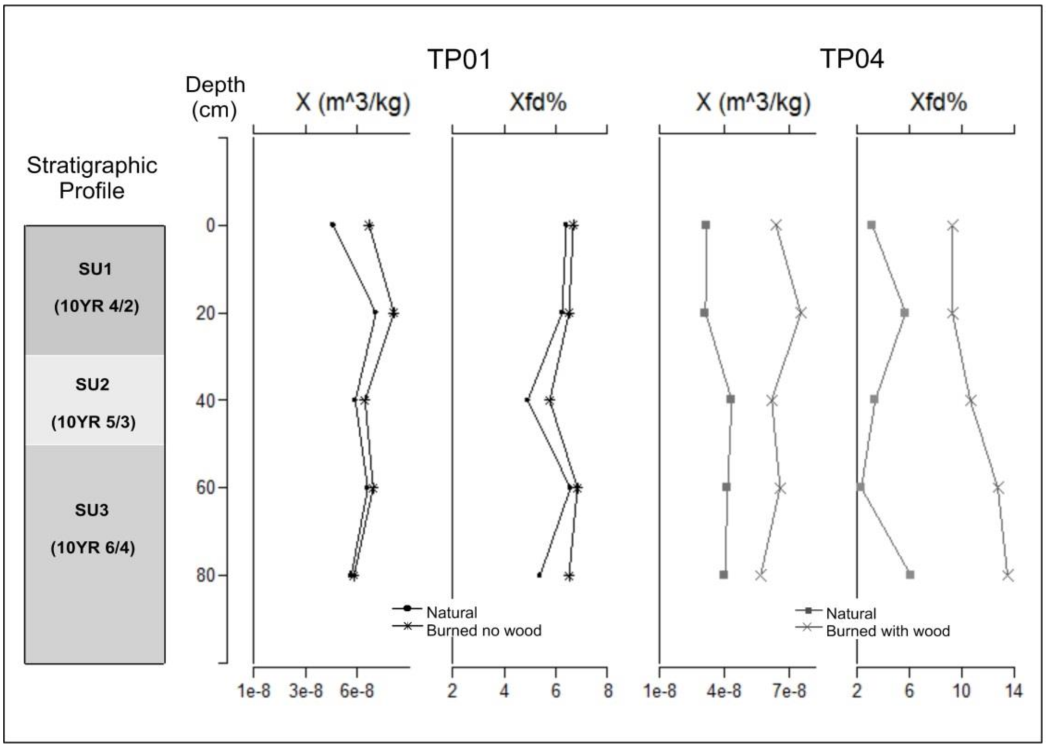

Figure 3.7 **Natural, burned without wood (black) and unburned (grey) profiles of low-field magnetic susceptibility and frequency dependence (overlapping values for TP02 and TP03 not shown). Experiments reveal wood fuel contributes significantly to increases in both parameters.**

3.5 Discussion and Conclusion

There is a strong relationship between the onset of human occupation at GS1 as defined by the stone artefacts and a change in the magnetic properties of the associated sediments. Beyond the overhang, it was expected that natural fire events, which are common in most Australian environments including the savannah land where the GS1 shelter is located, would result in changes to the magnetic properties of off-site sediments. However, none of the sediment samples from the test-pits displayed enhanced susceptibility or χfd%. In contrast, in all of the GS1 test-pits inside the overhang, increased magnetic susceptibility values and the onset of stable χfd% coincide with the level at which stone artefacts appear in the sedimentary sequence.

The obvious question deriving from these observations is, why do the sediments in archaeological sites have a much stronger magnetic response? The answer appears to be straightforward. Experimental data has shown that natural fires generally do not alter soil temperature and/or mineralogy as those sediments associated with fires in hearths (cf. Bellomo 1993; Linford and Canti 2001; McClean and Kean 1993). It was noted (Ketterings and Bigham 2000) that soil mineralogy is generally altered when fire temperatures exceed 400°C, for durations of 1 hour or more; these conditions are not typically met in forest fires. In forest fires, bark acts as an insulator, reducing the amount of heat transferred to the soil and, as a result, the surrounding sediments are rarely oxidised. Likewise, grass fires do not generate sufficient heat to cause mineralogical transformations in the soils (Bellomo 1993). Soil mineral alterations from forest fires only occur in restricted areas where fuel sources, such as logs and stumps, are concentrated (Ulery et al. 1996), a situation unlikely to occur in most rockshelters, or even on open sites such as shell middens. In contrast, humanly controlled hearth fires are often multiple use features that require a significant amount of fuel, that regularly burn for extended periods of time, and tend to maintain higher temperatures. The co-occurrence of enhanced magnetic susceptibility with human settlement is not coincidental.

The stable and relatively high χfd% is almost certainly a human artefact, but in this case it is also an Australian, or at least, an old craton, peculiarity. With a few exceptions (Worm 1998), χfd% readings of >15% are regarded as rare in environmental materials, and often result from weak, diamagnetic samples (i.e. quartz or feldspar dominated samples) (Dearing et al. 1996; Thompson and Oldfield 1986). High χfd% values are known from archaeological sites beyond Australia, typically caused by burning events and pedogenesis (Dalan and Banerjee 1998; Maher and Taylor 1988; Oldfield and Crowther 2007). At GS1, the χfd% (~10%) resembles percentages typical of modern soils rich in organic carbon. While most natural soils show a progressive decrease in the abundance of SP grains with depth (Lindquist et al. 2011), the samples at GS1 show consistently elevated and stable SP concentrations. This further indicates that the sediments are not an expression of natural environmental processes but that human occupation played an important role in the formation of the magnetic assemblage.

Again, the high χfd% values observed in the GS1 site sediments are not apparent in the off-site sediments beyond the overhang. High χfd% is also a measurement of the percentage of SP grains, and it is apparent that the burning in GS1 has not only increased the magnetic susceptibility values, but it has also increased the fine-grained component of the magnetic signature. Unlike younger geological landscapes, where ferromagnetic minerals are largely present as primary minerals, in old landscapes such as Australia, iron-rich minerals are present mainly in pedogenic forms, either as duricrusts, or very frequently as oxide and sesquioxide cutans on the outside of quartz grains (cf Singh et al. 1991). The combustion of wood in close proximity to these cutans, which themselves often contain organic chelates provides a source of iron to be converted to SD and SP grains by heating and oxidation (van Breemen and Buurman 2003).

We propose that the high and stable χfd% values observed in these Australian mineral magnetic samples is a trade-mark signature of this modification of Fe-bearing organic compounds, iron oxides and sesquioxide coatings, and can be used as a second (but not independent) proxy for human generated fires of high temperature and long duration. We argue that, while similar magnetic minerals (consisting of hematite and goethite) are present in the sediments both inside and beyond the overhang, the increases in magnetic enhancement are produced by anthropogenic burning of wood fuel and not pedogenesis or chemical weathering. While no combustion features were detected in the excavations, the rise in susceptibility and the distinctive temperature data are consistent with a human occupation that involved both burning and the incorporation of organic carbon. The nearly 2 m worth of consistently stable χfd% support this.

These findings are a critical new development in Australian archaeology, and also likely to be applicable to sites in other old cratonic landscapes elsewhere. While it has been shown that diamagnetic, very weakly magnetic weathered quartzose sands (Herries and Fisher 2010) become magnetically enhanced from burning, this is the first time that this characteristic has been used to define the presence of humans at a site in Australia. It provides a novel opportunity to re-examine early archaeological sites in northern Australia where the associations between dated sediments and stone artefacts are disputed (e.g. Madjedbebe, formally Malakunanja II) (O’Connell and Allen 2004) to determine the stratigraphic level at which camp fires become sufficiently prolific to categorically infer human presence. As such, it will finally provide unambiguous targets for luminescence dating and may contribute to resolution of the issue of first settlement of Australia, as well as contributing to understanding subsequent patterns of occupation (and posited abandonment) of sites through the LGM period (e.g. O’Connor et al. 1999).

Acknowledgements

We thank Mike Jackson and Dario Bilardello from the Institute of Rock Magnetism, University of Minnesota for their assistance and feedback regarding the magnetic analysis, and Rinita Dalan from

Minnesota State University Moorhead for helpful suggestions regarding the initial analysis. We also thank the Woolgar Valley Aboriginal Corporation for supporting this research, Flinders University and the Australian Institute of Aboriginal and Torres Strait Islander Studies for funding the GS1 excavations, all those involved in the fieldwork, and Aaron Fogel for comments to improve this manuscript. K.M.L. was funded by the Institute of Rock Magnetism, University of Minnesota Visiting Research Fellowship and the University of Queensland, through an International Postgraduate Research Scholarship and Centennial Scholarship, and a Graduate School International Travel Award.

3.6 Supplementary Material

Bivariate plots were again used to discern relative grain sizes and magnetic mineralogy concentrations within the stratigraphic profiles. For this section only Square C0 and D1 are provided to supplement those plots found in the paper. Like those found in Square C1, the ARM versus χ plot indicates an increase in the concentration of the magnetic carrier in the upper stratigraphic units (SUs 3–1) of Squares C0 (Figure 3.S1a) and D1 (Figure 3.S2a). Again the remaining samples appear to have little change in concentration, although the lower units of SU7 and SU8 reveal a slight change in concentration and perhaps grain size. All samples generally plot along the same line extending out from the origin, indicating a similar-sized magnetic material. The ARM versus SIRM plot, which is also used to look at dominate grain sizes and magnetic mineral concentrations also confirms this for Square C0 (Figure 3.S1b) and Square D1 (Figure 3.S2b).

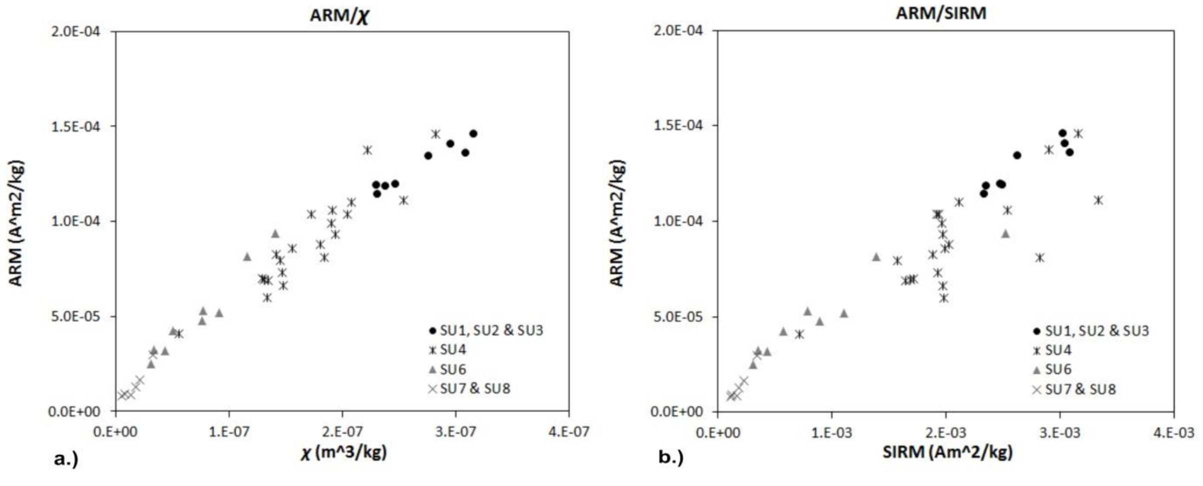

Figure 3.S1 Plots of (a) ARM susceptibility versus mass susceptibility and (b) ARM susceptibility versus SIRM susceptibility for Square C0 samples.

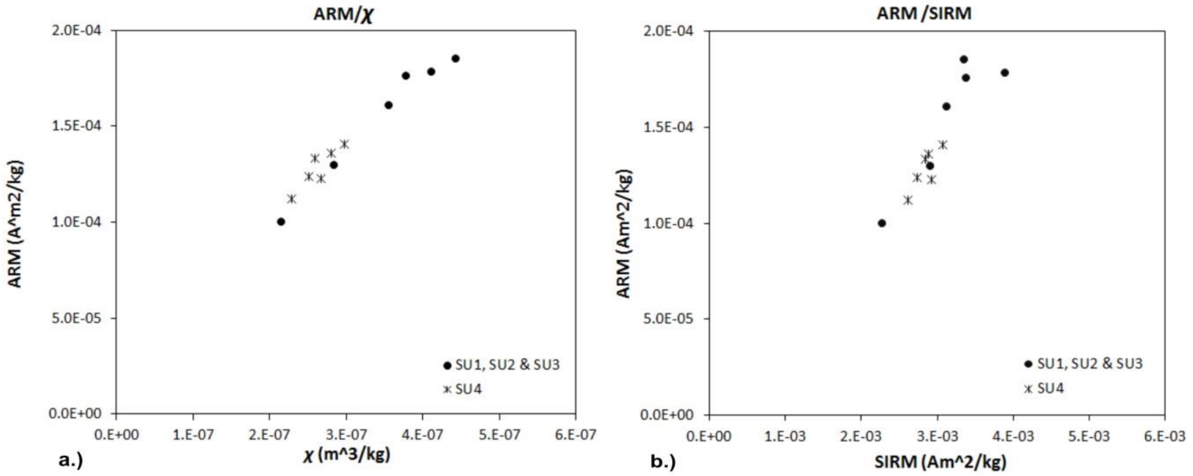

Figure 3.S2 Plots of (a) ARM susceptibility versus mass susceptibility and (b) ARM susceptibility versus SIRM susceptibility for Square D1 samples.

Bivariate plots of Mr/Ms versus Hc were used to look grain size and composition. The samples fall squarely between the reference line between pure magnetite and TM60 (Figure 3.S3).

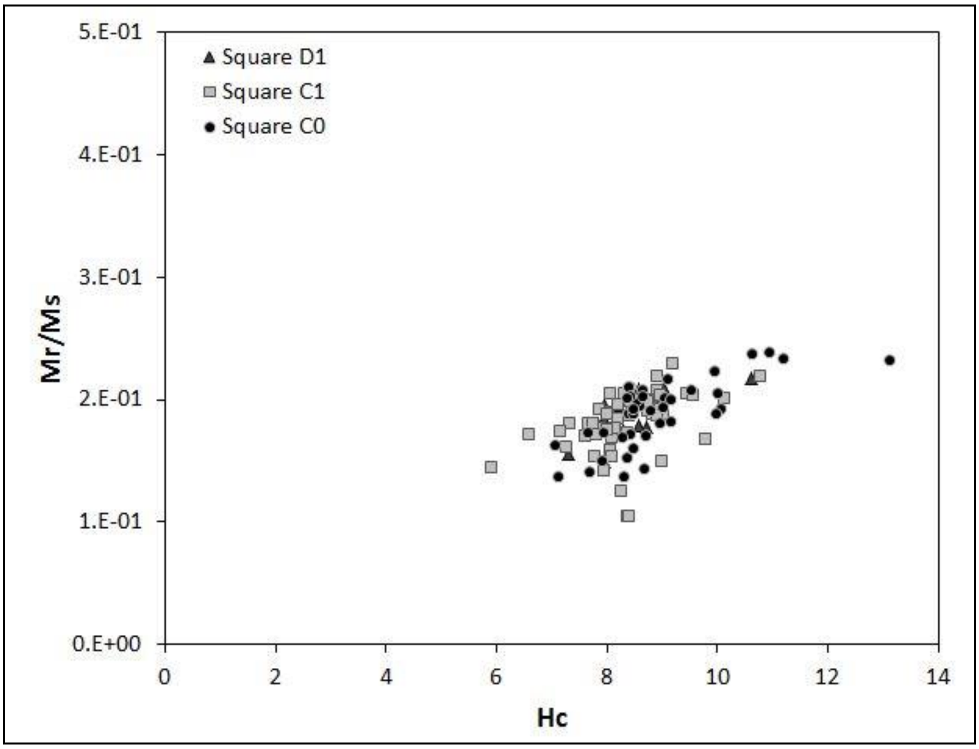

Figure 3.S3 Plot of Mr/MS coercivity versus Hc coercivity for Squares C0, C1 and D1.

Bivariate plots of χ to mass-specific frequency-dependent susceptibility (χlf-χhf) show a positive and linear relationship, supporting substantial SP concentrations (Figure 3.S4a) (Dearing et al. 1996; Evans and Heller 2003). Room temperature measurements using four frequencies on the

Quantum Design MPMS2-52 corroborate this (Figure 3.S4b). These results demonstrate that the dominant magnetic grain size is very fine (hence SP).

Controlled burn experiments in a lab using different temperatures (>400°C) for 1 hour on the 'off-site' test pits also indicated that wood fuel contributes significantly to increases in χ and χfd% (Sup Figure 3.S5). Again, burns where wood fuel was not added to the sample indicated little change in χ and alterations only in colour, which changed to reddish yellow (7.5YR 6/6). Samples subjected to burning with a fuel source increased up to three magnitudes (see also Figure 3.7 in text).

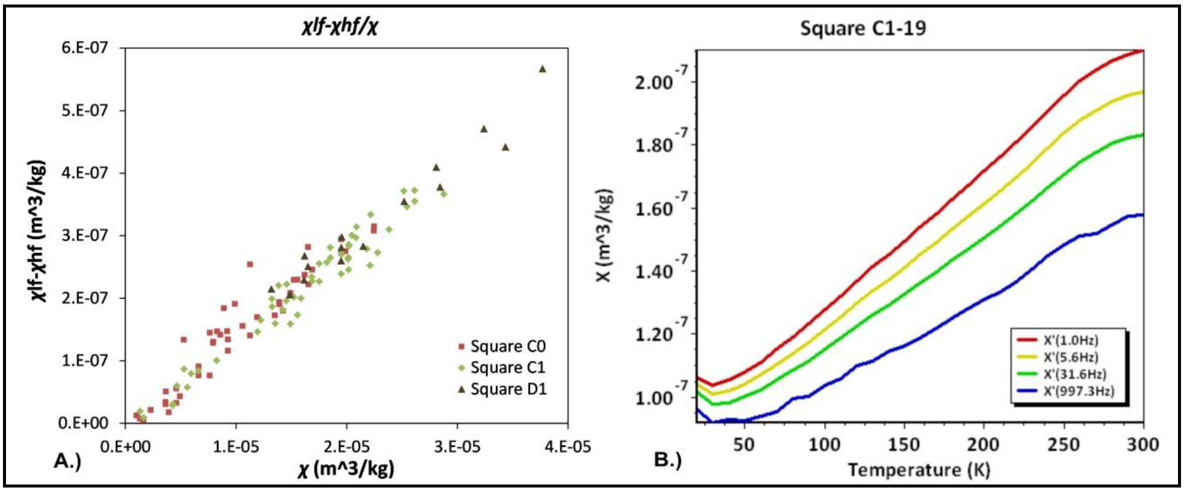

Figure 3.S4 Plots of (a) mass-specific frequency-dependent susceptibility versus susceptibility, indicating a positive and linear relationship and (b) room temperature measurements using several frequencies, confirming a significant nanoparticle population.

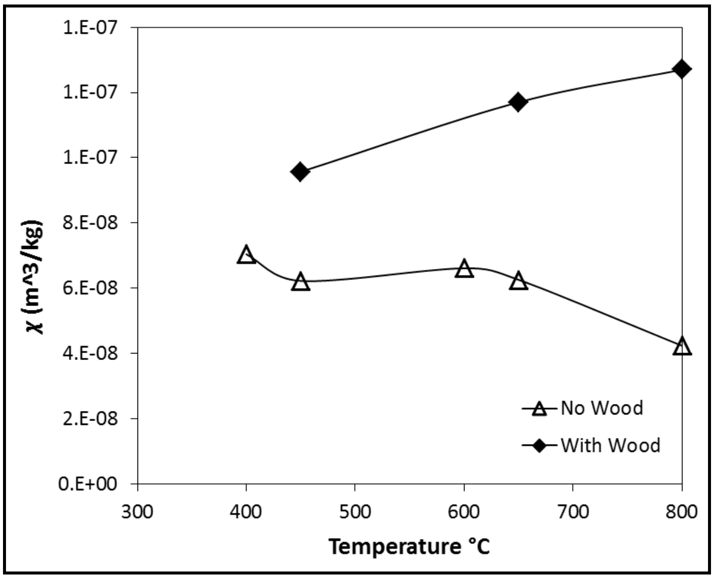

Figure 3.S5 Controlled burn examples on 'off-site' test pits (TP01 – no wood, TP02 – with wood) revealing changes in magnetic susceptibility with temperature increases. Note magnetic susceptibility increases when fuel source was added, while samples without wood revealed decreasing magnetic susceptibility values.

References

Banerjee, S. K. 1981 Experimental methods of rock magnetism and paleomagnetism. In B. Saltzman (ed.), *Advances in Geophysics, Vol. 23*, pp. 25–99. New York: Academic Press.

Bellomo, R. V. 1993 A methodological approach for identifying archaeological evidence of fire resulting from human activities. *Journal of Archaeological Science* 20:525–553.

Carah, X. 2010 *Corridors and Callitris: Examining the Changing Use of Environment, Through the Gledswood Shelter 1 Wood Charcoal Assemblade*. Unpublished Honour's Thesis, School of Social Science, The University of Queensland, St Lucia.

Carrancho, Á. and J. J. Villalaín 2011 Different mechanisms of magnetisation recorded in experimental fires: Archaeomagnetic implications. *Earth and Planetary Science Letters* 312(1–2):176–187.

Dalan, R. A. 2006 A geophysical approach to buried site detection using down-hole susceptibility and soil magnetic techniques. *Archaeological Prospection* 13:182–206.

Dalan, R. A. and S. K. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13:3–36.

Dearing, J. A., K. L. Hay, S. M. J. Baban, S. A. Hudleston, E. M. H. Wellington and P. J. Loveland 1996 Magnetic susceptibility of soil: An evaluation of conflicting theories using a national data set. *Geophysics Journal International* 127:728–734.

Evans, M. E. and F. Heller 2003 *Environmental Magnetism: Principles and Applications of Enviromagnetics*. London: Academic Press.

Ellwood, B. B., K. M. Petruso, F. B. Harrold and J. Schuldenrein 1997 High-resolution paleoclimatic trends for the Holocene identified using magnetic susceptibility data from archaeological excavations in caves. *Journal of Archaeological Science* 24:569–573.

Forster, P., A. Torroni, C. Renfrew and A. Röhl 2001 Phylogenetic star contraction applied to Asian and Papuan mtDNA evolution. *Molecular Biology and Evolution* 18:1864–1881.

Geoscience Australia 2004 GEODATA COAST 100K 2004: Product User Guide. National Mapping Division. Canberra: Australian Government.

Hanesch, M., H. Stanjek and N. Petersen 2006 Thermomagnetic measuresments of soil iron minerals: The role of organic carbon. *Geophysical Journal International* 165:53–61.

Herries, A. I. R. and E. C. Fisher 2010 Multidimensional GIS modeling of magnetic mineralogy as a proxy for fire use and spatial patterning: evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution* 59:306–320.

Jackson, M., H. U. Worm and S. K. Banerjee 1990 Fourier analysis of digital hysteresis data: Rock magentic applications. Physical Earth Planetary International 65:78–87.

Kershaw, A., G. McKenzie and A. McMinn 1993 A Quaternary vegetation of northeastern Queensland from pollen analysis of ODP site 820. In Proceedings of the Ocean Drilling Program. *Scientific Results* 133:107–114.

Ketterings, Q. M. and J. M. Bigham 2000 Soil color as an indicator of slash-and-burn fire severity and soil fertility in Sumatra, Indonesia. *Soil Science of American Journal* 64:1826–1833.

King, J. W., S. K. Banerjee, J. Marvin and Ö. Özdemir 1982 A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: Some results in lake sediments. *Earth and Planetary Science Letters* 59:404–419.

Le Borgne, E. 1955 Susceptibilite magnetiqe anormale de sol superficiel. *Annales de Geophysique* 11:399–419.

Lindquist, A. K., J. M. Feinberg and M. R. Waters 2011 Rock magnetic properties of a soil developed on an alluvial deposit at Buttermilk Creek, Texas, USA. *Geochemistry, Geophysics, Geosystems* 12(12): Q12Z36, doi: 10.1029/2011gc003848.

Linford, N. T., P. Linford and E. Platzman 2005 Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames valley, United Kingdom. *Journal of Archaeological Science* 32(7):1037–1043.

Linford, N. T. and M. G. Canti 2001 Geophysical evidence for fires in antiquity: Preliminary results from an experimental study. Paper given at the EGS XXIV General Assembly in The Hague, April 1999. *Archaeological Prospection* 8:211–225.

Longworth, G. and M. S. Tite 1977 Mossbauer and magnetic susceptibility studies on iron oxide in soils from archaeological sites. *Archaeometry* 19:3–14.

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84.

Maher, B. A. 1986 Characterisation of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interior* 42:76–92.

Maher, B. A. and R. M. Taylor 1988 Formation of ultrafine-grained magnetite in soils. *Nature* 336:368–371.

Maki, D., J. A. Homburg and S. D. Brosowske 2006 Thermally activated mineralogical transformations in archaeological hearths: Inversion from maghemite Fe_2O_4 phase to haematite Fe_2O_4 form. *Archaeological Prospection* 13:207–227.

McClean, R. G. and W. F. Kean 1993 Contributions of wood ash magnetism to archaeomagnetic properties of fire pits and hearths. *Earth and Planetary Science Letters* 119:387–394.

Morinaga, H., H. Inokuchi, H. Yamashita, A. Ono and T. Inada 1999 Magnetic detection of heated soils at paleolithic sites in Japan. *Geoarchaeology* 14(5):377–399.

O'Connell, J. F. and J. Allen 2004 Dating the colonization of Sahul (Pleistocene Australia–New Guinea): A review of recent research. *Journal of Archaeological Science* 31:835–853.

O'Connor, S., P. Veth and A. Barham 1999 Cultural versus natural explanations for lacunae in Aboriginal occupation deposits in northern Australia. *Quaternary International* 59:61–70.

Oldfield, F. and J. Crowther 2007 Establishing fire incidence in temperate soils using magnetic measurements. *Palaeogeography, Palaeoclimatology, Palaeoecology* 249:362–369.

Rayment, G. E. and D. J. Lyons 2011 *Soil Chemical Methods – Australasia*. CSIRO Publishing, Collingwood.

Singh, B., S. O’Connor, P. Veth and R. Gilkes. 1991 Detection of amorphous alumino-silicate by x-ray diffraction and chemical analysis to detect firing in archaeological sediments. *Archaeology in Oceania* 26(1):17–20.

Stevens, N. C. 1972 *Geology and Landscape of Queensland*. Melbourne: Jacaranda Press, Pty, Ltd.

Thompson, R. and F. Oldfield 1986 *Environmental Magnetism*. London: Allen and Unwin.

Thorne, A., R. Grün, G. Mortimer, N. A. Spooner, J. J. Simpson, M. McCulloch, L. Taylor and D. Curnoe 1999 Australia's oldest human remains: Age of the Lake Mungo 3 skeleton. *Journal of Human Evolution* 36:591–612.

Tite, M. S. and C. Mullins 1971 Enhancement of the magnetic susceptibility of soils on archaeological sites. *Archaeometry* 13:209–219.

van Breemen, N. and P. Buuman 2003 *Soil Formation*. New York: Kluwer Academic Publishers.

Ulery, A. L., R. C. Graham and L. H. Bowen 1996 Forest fire effects on soil phyllosilicates in California. *Soil Science Society of American Journal* 60:309–315.

Wallis, L. A., B. Keys, I. Moffat and S. Fallon 2009 Gledswood Shelter 1: Initial radiocarbon dates from a Pleistocene aged rockshelter site in northwest Queensland. *Australian Archaeology* 69:71–74.

Worm, H.-U. 1998 On the superparamagnetic—stable single domain transition for magnetite, and frequency dependence of susceptibility. *Geophysical Journal International* 133:201–206.

CHAPTER 4

THE LATE QUATERNARY IN INTERIOR NORTHEASTERN AUSTRALIA: HUMAN OCCUPATION THROUGH THE LAST GLACIAL MAXIMUM

Chapter 4 is reproduced from the article submitted to *Quaternary Science Reviews* and is part of the thesis question regarding human occupation during the LGM. It has been reformatted for this thesis chapter.

Lowe, K. M., S. Mentzer, L. A. Wallis and J. Shulmeister The late Quaternary in interior northeastern Australia: Human occupation through the Last Glacial Maximum. Submitted to Quaternary Science Reviews in July 2014.

4.1 Abstract

Understanding the nature of climate change and its effects on people during Marine Isotope Stages 3 and 2 in the interior of northern Sahul (Australia-New Guinea) is challenging due to the scarcity of suitable palaeoenvironmental study sites and the stratigraphic complexity of the archaeological rockshelters that form our primary source of information. Gledswood Shelter 1 (GS1), which was first occupied at ca 38,000 BP, to the west of the Great Dividing Range in the inland northeast of the continent, is situated in a region that has been characterised as a potential corridor for early colonists moving into the arid interior. Magnetic susceptibility and micromorphology techniques were integrated with geoarchaeology, soil chemistry and geochronology at GS1 to better understand the history and formation processes of the site. The micromorphology studies indicate that primary depositional fabrics, such as graded bedding or laminations, are generally absent, and structural development is low throughout the entire sequence, with most samples exhibiting a massive structure. An increase in magnetic susceptibility values are associated with anthropogentic burning, and the first appearance of stone artefacts, indicating another proxy for determining human occupation. Major changes in the cultural components of the site are apparent in the early and mid-Holocene, the latter coinciding with the onset of El Niño/Southern Oscillation activity. The use of GS1 through the last glacial maximum implies the availability of water at the site, which is suggestive of the monsoon driven by the Coral Sea still being active during this time.

4.2 Introduction and Aims

For nearly half a century there has been ongoing debate regarding the timing and nature of colonisation of Sahul (Australia-New Guinea) by anatomically modern humans (Allen and O’Connell 2003; O’Connell and Allen 2004), along with discussion about how and when people adapted to the multitude of biogeographic regions present (Bowdler 1977; Fifield et al. 2001; Hiscock 2008:45; Smith 1989, 1993; Veth 1989). These debates are critical to understanding the development of modern behavioral patterns, and are thus relevant for furthering our knowledge about broader debates around the emergence and migration of modern humans from Africa. While Birdsell (1957) originally suggested colonisation of the entire continent took humans only a couple of thousand years, Bowdler (1977) argued on the basis of patterning in the then-current archaeological database that people were better adapted to maritime environments and initially focused their attention on coastal and major riverine systems. However, the subsequent demonstration that early sites were also present elsewhere led to alternative suggestions about colonists utilising non-coastally specific social and economic skills to address the challenges presented by the arid and semi-arid zones of the continent (Bowler et al. 2003; Horton 1981; Smith 1993; Veth 1989).

A key component of the debate has also been the nature and persistence of occupation of sites through the last glacial maximum (LGM) (Magee and Miller 1998; Magee et al. 1995; Petherick et al. 2011; Williams et al. 2009). While some sites exhibited persistent and intensified occupation during the LGM (e.g. Hiscock 1988; Lamb 1996; Marwick 2002; Smith 1989, 2009), others have no evidence of cultural material during that time, suggesting abandonment of the local environment (Hiscock 2008; O'Connor et al. 1999; Veth 1989). Veth (1989:81) argued the observed archaeological patterns fit a biogeographical model of continuous occupation of some well-watered 'refuges' within otherwise arid habitats during the terminal Pleistocene with widespread episodic versus repeated use of the remainder of the arid interior through the LGM (cf. Hiscock and Wallis 2005; Williams et al. 2013).

Given the geologically ancient Australian landscape, propositions about how and when people colonised different biogeographic zones are based, with only a few exceptions (e.g. Bowler and Price 1998; Veth et al. 2009), on sedimentary and environmental archives preserved in rockshelter sites. Issues of stratigraphy, particularly recognising and dating discrete episodes of human occupation, are key to the effective utilisation of such archives (Farrand 2001; Stein and Farrand 2001; Woodward and Goldberg 2001) though, isolating individual occupation surfaces is difficult because of the reoccurrence of habitation (Bailey 2007; Straus 1990:266). Methodological challenges in sediment analysis as well as the lack of preserved archaeological material particularly in low density sites, have also been issues regarding stratigraphy (O'Connor et al. 1999; Straus 1990; Ward and Larcombe 2003). Ongoing use of a site may also result in vertical displacement of artefacts, a consequence of human trampling or bioturbation (cf. David et al. 2007; Gifford-Gonzalez et al. 1985; Hughes and Lampert 1977; Nielsen 1991; Richardson 1992, 1996).

The study of the magnetic susceptibility of sediments has been widely adopted as a means through which to explore issues of the intensity of occupation of rockshelter and cave sites (Ellwood et al. 1997; Ellwood et al. 2004; Herries 2006; Herries and Fisher 2010). Magnetic susceptibility is a measure of the ease with which a material can be magnetised in the presence of a magnetic field (Thompson and Oldfield 1986:25), and can thus be used to detect the magnetic minerals present in sediments (Evans and Heller 2003). Iron minerals are the primary cause for magnetic enhancement and their presence can be due to both cultural or natural processes (i.e. fires, pedogenesis or chemical weathering) (Dalan and Banerjee 1998; Fassbinder et al. 1990; Le Borgne 1960; Linford et al. 2005; Maher and Taylor 1988). While only a few such studies have been completed on Australian sites (e.g. Davidson et al. 1993; Keys 2009; Marwick 2005), globally they have shown to be important tools for understanding past human occupation and environmental changes in Pleistocene rockshelter and cave deposits.

Presently, there are limited sites in the interior of Australia through which to understand human behaviour through Marine Isotope Stages (MIS) 1–3 (Allen and O’Connell in press): Gledswood Shelter 1 (GS1) is one such site (Wallis et al. 2009). Unlike many other late Pleistocene rockshelter sites in Australia, GS1 does not appear to be an obvious place for early or continuous settlement owing to its lack of water sources and limited living space (though the area in front of the overhang is well protected from the sun and sheltered from wind on most days). This site affords an opportunity to contribute to debates about how people spread across Australia and responded to climate changes through the late Quaternary. Our paper presents a comprehensive study of how geoarchaeological analysis with emphasis on magnetic susceptibility and micromorphology were used. Firstly to determine if sediments in GS1 were largely anthropogenic and whether they could provide information on the archaeological record, and secondly if a paleoenvironmental signal exits and if so, can it tell us about the nature and persistence of human occupation particularly during the LGM. While these approaches have shown to be quite complementary, few studies exist that utilise both (cf. Ajas et al. 2013; Marmet et al. 1999) and to date, none have been documented in Australia. Therefore, this study also highlights their importance in understanding anthropogenic inputs specifically in low-density sites, as well as formation processes of stratigraphically complex sites.

4.3 Environmental and Geomorphic Setting

The GS1 site is located in semi-arid tropical inland northeast of Sahul, on the west of the Great Dividing Range in contemporary northwest Queensland (Wallis et al. 2009) (Figure 4.1a). The local bedrock is the Jurassic fluvial and shallow water marine coarse Hampstead Sandstone of the Blythesdale Group that formed part of a thick sequence of sediment infilling the paleo-Carpentaria Basin (Smart 1973:12) (Figure 4.1b). Regional uplift began in the Late Cretaceous, with higher rates in the east. In combination with downwarping of the Carpentaria Basin, the uplift has resulted in the establishment of north-south trending faults expressed on the modern land surface as a series of plateaus bounded on their western flanks by escarpments. The south-facing GS1 overhang occurs in the westernmost of these escarpments, 480 m above sea level (asl). The site is located at a topographic boundary, with the foothills of the Gregory Ranges (600–900 m asl) to the east, and the Strathpark Plains (300–400 m asl) sloping gently to the west and south. Meandering their way across the Strathpark Plains, the Norman River is located 1.5 km to the south of GS1, while the Woolgar River is located 25 km to the southeast. The headwaters for both are in the Gregory Ranges, and both ultimately drain westward into the Gulf of Carpentaria (Figure 4.1a).

The soil temperature regime is isohyperthermic, with an average maximum summer air temperature of 34.5°C and an average maximum winter temperature of 26°C (Bureau of Meteorology 2013). The area has a semi-arid soil moisture regime, with annual rainfall averaging 480 mm (Bureau of Meterology 2013). The local thin, weakly developed soils are classified within the Tenosol order of the Australian Soil Classification system, characterised by A-horizons atop either unweathered parent material or weak B-horizons containing less than 15% illuvial clay. In the immediate vicinity of the site, the soil parent material is the sandstone bedrock with a quartz sand sheet abutting the shelter wall. Active soil modification processes in and around GS1 include surface hollowing by macropods, cattle and pigs, and termite activity. The surrounding vegetation primarily comprises Georgetown box (*Eucalyptus microneura*) woodland, with lancewood (*Acacia shirleyi*) and ironwood (*Erythophleum chlorostachys*). Other common species include quinine bush (*Petalostigma banksii*), *Bauhinia cunninghamii*, *Dolichandrone heterophylla*, *Carissa lanceolata*, *Terminalia* spp. and *Melaleuca* spp. The grass layer is dominated by a mixture of three-awn (*Aristida* spp.), ribbon (*Chrysopogon fallax*), blue (*Dicanthium* spp. and *Bothriochloa* spp.), kangaroo (*Themeda australis*) and spear grasses (*Heteropogon contortus*), with rocky areas dominated by spinifex (*Triodia* spp.).

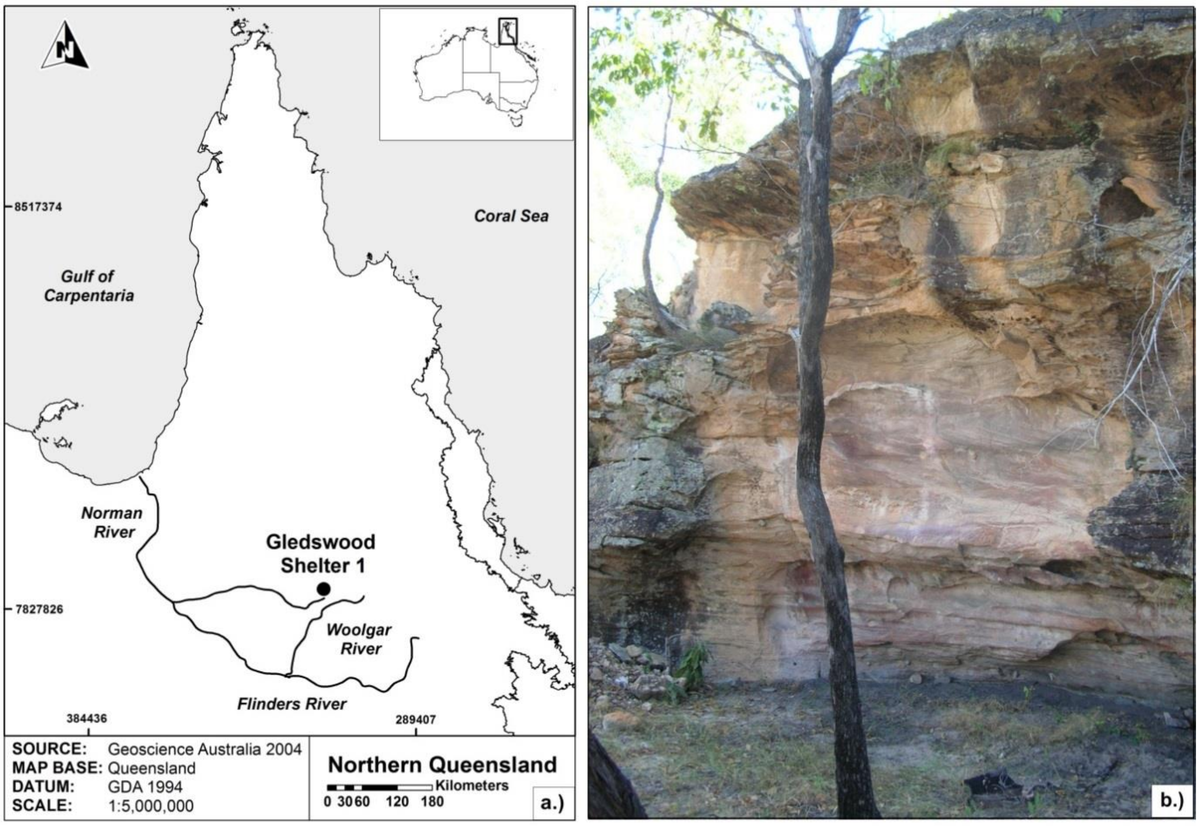

Figure 4.1. Map (a) showing the location of Gledswood Shelter 1 in northern Australia and (b) image of shelter today.

4.3.1 Regional Environmental History

There are no local paleoenvironmental histories available for the immediate study region. The nearest long-term records are from the Atherton Tablelands to the northeast (e.g. Kershaw et al. 1997) and marine cores from the Gulf of Carpentaria (e.g. Reeves et al. 2007, 2008) north-northwest of GS1; however, these sites are many hundreds of kilometres away and are in areas of higher rainfall. The Atherton is particularly atypical of northern Australia because it receives considerable orographic rainfall in the dry season from southeast trade winds coming off the Coral Sea. The most robust records of monsoonal rainfall levels come from the Lake Eyre Basin in South Australia, a system which is fed largely by tropical moisture (Magee and Miller 1998; Magee et al. 1995). Records from Indonesia and off the northwest coastline of Australia are also helpful in determining the status of the Australian Monsoon (e.g. Lewis et al. 2011; Spooner et al. 2005; van der Kaars et al. 2000)

In summary, published records suggest that effective precipitation (EP) in Sahul was higher in the period between 35–30 ka but with the monsoon largely inactive between 30–25 ka (Reeves et al. 2013; Spooner et al. 2005; van der Kaars et al. 2000). In contrast, there is some evidence for enhanced EP from rainforest expansion on the Atherton Tablelands between ca 26 and 24 ka, which suggests additional moisture in the northeast of Australia. There is little detailed evidence from northern Australia regarding climate at the LGM (22–18 ka) but, like elsewhere in Australia, it is assumed to be cooler and especially drier at this time (Reeves et al. 2013). The post-LGM period is inferred to be dry across much of the tropical north with dry plunge pools (Nott and Price 1999) and low lakes levels (Harrison 1993). After 15 ka the monsoon began to become more effective across northern Australia with shelves flooding, and by 12 ka monsoon rains were being transmitted to Lake Eyre (Magee et al. 1995).

The Holocene is inferred to exhibit a diachronically bimodal climate in northern Australia. The early Holocene is associated with reliable and higher rainfall as evidenced by active plunge pools (Reeves et al. 2013). The latter part of the Holocene is characterised by increased variability in precipitation relating to the intensification of El Niño/Southern Oscillation (ENSO) activity (McGlone et al. 1992; Shulmeister and Lees 1995; see also Prebble et al. 2005).

4.3.2 The Study Site

The GS1 shelter is a small overhang formed as a result of cavernous weathering (tafoni[1]) at the base of a weathered 8 m high Mesozoic sandstone outcrop, surrounded by several sandstone outliers and outcrops of exposed bedrock (Figure 4.2). The shelter is located on the outcrop's southern face and the interior space is about 7 m wide, with a height to the roof of 3–5 m at the drip-line, and a maximum depth of 3 m from the back wall to drip-line. Stencilled art and pecked geometric motifs occur on the walls of the shelter, and the shelter floor is comprised of sandy and silty sediments that cover about 20 m² and support minimal vegetation. Beyond the drip-line the lightly wooded ground surface extends 60 m south and west from the outcrop before dropping down about 15 m on to the Strathpark Plains.

Six adjoining 1 x 1 m test pits (Squares B0, B1, C0, C1, D0 and D1) were excavated in arbitrary ~5 cm excavation units (XUs) or spits in the area between the shelter wall and drip-line, to a maximum depth of ca 2.6 m below surface. Square C1 is the main square discussed in this paper. Stratigraphic units (SU) were defined on the basis of textural and sediment morphological characteristics (Figure 4.3 and Table 4.1). The units are broadly horizontal, with two depositional areas defined. First, the deposits in the more southerly excavation squares are dominated by large quantities of sandstone gravel and cobbles that appear to have fallen from the top of the outcrop onto the ground just

---

Tafoni features typically form in arid environments due to salt weathering and other wetting and drying processes, combined with differential permeability and instability of bedded, clastic bedrock (Mol and Viles 2012; Turkington and Paradise 2005). [1]

forward of the drip-line (see below). Second, lateral facies changes associated with the morphology of the backwall and living space have resulted in division of the middle sequence into units proximal (SU6a) and distal (SU6b) to the rear wall. The sediment pH for all SUs is acidic, consistently ranging from 5–6 throughout the sequence.

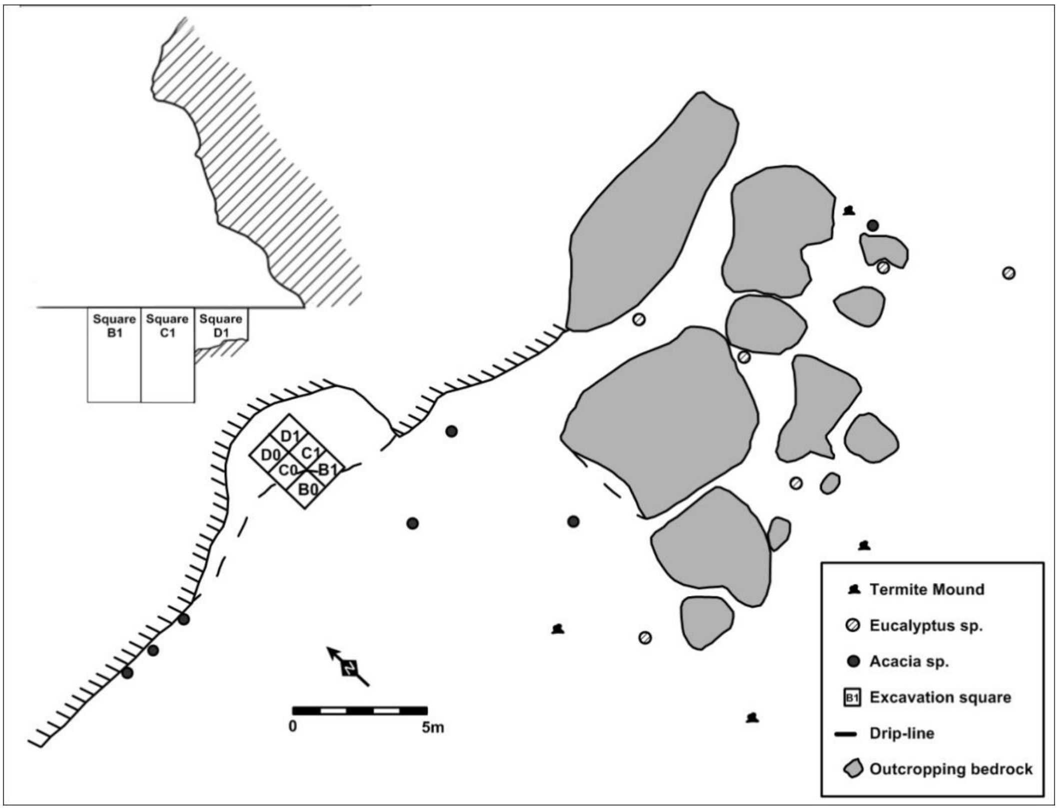

Figure 4.2 Site plan map of GS1, showing excavations, shelter dimension and drip-line (Wallis et al. 2009:Figure 1).

SUs 8 and 7 are culturally sterile, with stone artefacts first appearing in low quantities in the middle of SU6, and increasing substantially in abundance by the top of this unit. Stone artefacts are present through all overlying units in varying quantities, as are fragments of ochre and charcoal (Carah 2010). Other remains, such as bone and organics, are minimal owing to the poor preservation conditions.

The site was dated initially using radiocarbon on wood charcoal, demonstrating sedimentation in the site commenced ca 40,000 years ago, with initial human presence from 38,000 BP (Table 4.2). Radiocarbon ages for GS1 were calibrated using OxCal v.4.2 (Bronk Ramsey, 2009) against SHCal13 (Hogg et al., 2013), with all calibrated ages reported at the 95.4% confidence level. Samples were also collected for optically stimulated luminescence (OSL) dating, with single aliquot dating undertaken by Kathryn Fitzsimmons in the Research School of Earth Sciences at The Australian National University. These were followed up by single grain dating in the Department of Human Evolution at the Max Planck Institute for Evolutionary Anthropology; OSL results are being assessed in conjunction with the micromorphological evidence for changes to the water regime in the pre-LGM period associated with the site and will be presented elsewhere (see Wallis et al. unpub data).

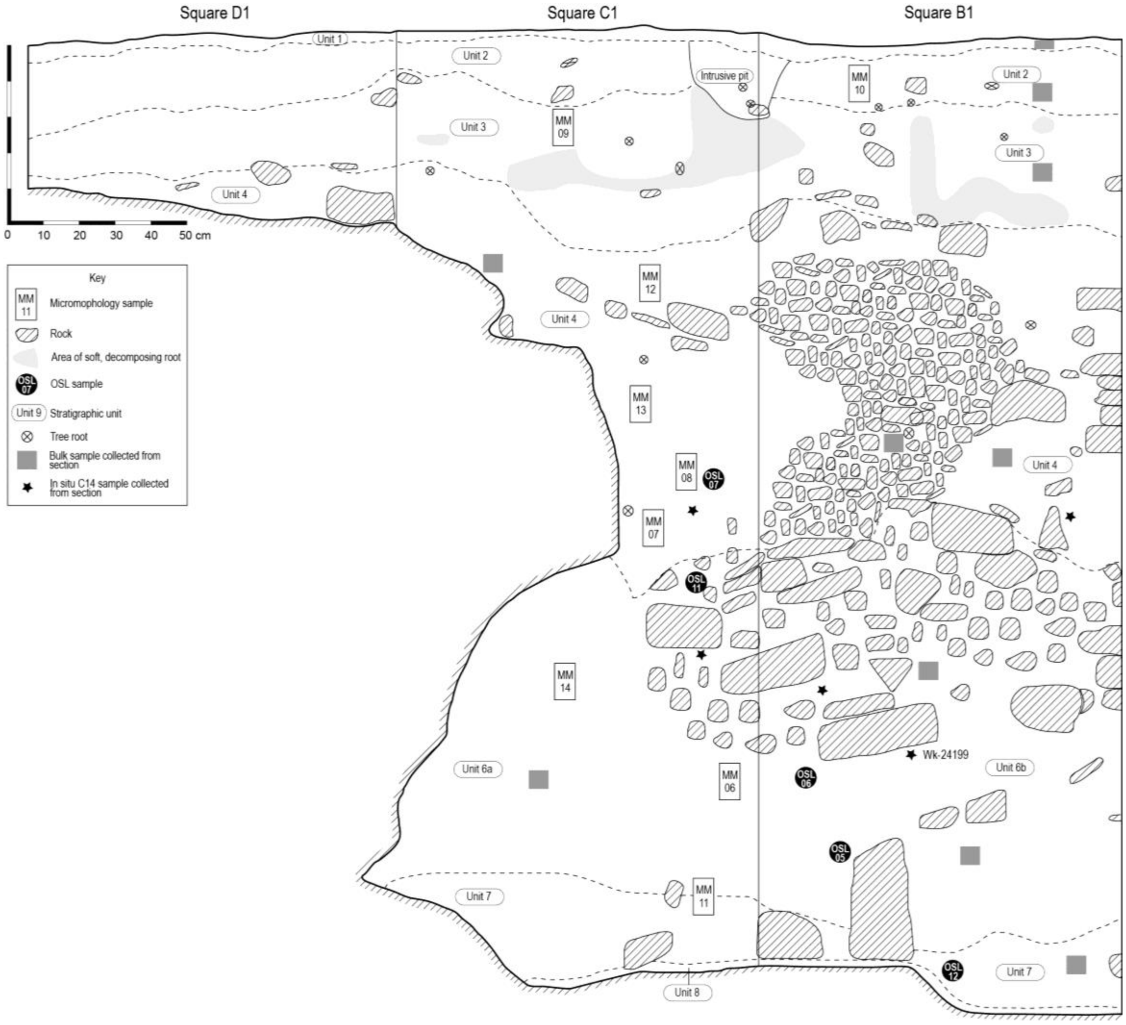

Figure 4.3 Stratigraphic west wall section profiles of Squares D1, C1 and B1.

Table 4.1 Sedimentary description for GS1 stratigraphic units.

STRATIGRAPHIC UNIT(SU)	DEPTH (cm below surface)	DESCRIPTION
SU1	0–5	Dark grey (10YR 4/1), loose, poorly to moderately sorted, subangular medium sand with few charcoal fragments and leaf litter. pH is 5.
SU2	5–20	Dark grey to very dark grey (10YR 4/1–3/1), poorly to moderately sorted, subangular fine-medium sand. Moderately compacted with small roots and holes. Charcoal is abundant. Sandstone rocks are present, but only in areas below the drip-line. pH is 5.
SU3	20–50	Very dark grey (10YR 3/1), poorly sorted, subangular medium sand with abundant charcoal. Moderately compacted with small roots and holes. Sandstone rocks are present, but only in areas below the drip-line. pH is 5.
SU4	50–155	Compacted, poorly to moderately sorted, fine-medium sand rich in archaeological material. Lower levels are brown (10YR 4/3) overlain by dark greyish brown (10YR 4/2). Large quantities of sandstone rock fragments are present in areas below the drip-line. pH ranges from 5–5.5.
SU6a and b	155–232	Subunit 6a is the area of deposit underneath the overhanging bedrock which contains only very small quantities of stone artefacts, while Subunit 6b is the area of deposit beyond the overhanging bedrock. Light yellowish brown (10YR 6/4), poorly sorted, subangular medium sand. Large rounded cobble-sized fragments of sandstone are present in Subunit 6b. pH ranges from 5–5.5. The lower portion of SU6 is entirely culturally sterile.
SU7	232–250	Culturally sterile, dry, homogeneous reddish yellow (7.5YR 6/6) to pink (7.5YR 8/4) poorly sorted, sub-angular medium-coarse sand. pH is 5.5.
SU8	250–260	Culturally sterile, very thin, talc-like light grey (10YR 7/1) sand. pH is 5.

Table 4.2 Unpublished radiocarbon dates at GS1.

LAB NUMBER	SQUARE	DEPTH (cm below surface)	SU	^{14}C AGE	±	CALIBRATED AGE BP (95.4% probability)
ANU-2625	C0	25	3	1530	35	1303–1469
ANU-2629	C0	47	4	3525	40	3697–3973
Wk-33293	B1	74	4	4808	64	5321–5607
Wk-33294	B1	129	4	10786	189	12,074–13,055
Wk-33296	C1	140	4	10354	34	11,845–12,390
Wk-33292	B1	163	6b	14464	235	16,915–18,160
Wk-33295	B1	168	6b	15020	45	18,000–18,369
OZM095	C1	170	6a	14950	80	17,904–18,350
OZM096	C1	175	6	22180	130	26,017–26,738
OZM094	C1	205	6	32730	290	35,992–37,764

4.4 Material and Methods

Detailed sedimentary analysis at GS1 focused on Square C1 and included sedimentological description, particle size analysis, loss on ignition (LOI), available phosphorous analysis (P), phytolith analysis, micromorphology and analyses of magnetic mineralogies. Correlations between the datasets were then assessed to help distinguish cultural from natural inputs to the archaeological deposit and to resolve the issue of when people first began visiting the site and whether they were present leading into and during the peak of the LGM.

4.4.1 Magnetic Susceptibility

Both mass and volume low-field magnetic susceptibility (χ and K) were taken, as well as dual frequencies for frequency dependence of susceptibility (χfd%). These measurements were followed with anhysteretic remanent magnetisation (ARM), saturation isothermal remanent magnetisation (SIRM), hysteresis loops, and high and low temperature tests at the Institute of Rock Magnetism (IRM) at the University of Minnesota. High (Curie point) and low temperature measurements of the sediments were then made on selected samples, primarily those exhibiting magnetic enhancements within each stratigraphic unit, though a few weakly magnetic samples were also selected for comparative purposes. Full details of the magnetic susceptibility methods and results are presented in Lowe et al. (in review).

4.4.2 Particle Size and Organic Content

The dry sieving method of particle size analysis followed that of Ingram (1971) and McManus (1988) (for details see Keys 2009). Pre-treatment involved ashing each sample for ~12 hours in a muffle furnace at 450ºC to remove any organics and measure LOI values. Each sample was then screened through nested Endecotts sieves [1.00–500 µm (medium to coarse sand), 500–250 µm (fine sand), 250–125 µm (very fine sand) and 125–63 µm (silt and clay)] using a Geolab Systems mechanical sieve shaker. Laser granulometry was attempted on some of the samples; however, given the very small quantities of clays and silts present, it was not considered worthwhile to pursue it further.

4.4.3 Phosphorus and Phytoliths

Subsamples for available P analysis were taken from each spit, air-dried and sieved through a 2 mm mesh. Phosphorus extraction and measurement was done using a Mehlich 3 extraction technique (after Rayment and Lyons 2011:398–402) which is used for sediments high in iron and/or aluminum. This was completed in the School of Agriculture and Soil Science at The University of Queensland using a Varian Vista Port ICPOES (inductively coupled plasma optical emission spectrometry) instrument. The phytoliths were extracted by using an ashing technique (adapted from Bowdery 1998). Samples were first oven dried at 70ºC for 24 hours and then sieved through a 1 mm mesh sieve. Approximately ~7 g of sediment was placed in lidded porcelain crucibles and weighed before being ashed in a muffle furnace at 450 ºC for 24 hours. The ashed material was then washed with hydrogen peroxide to remove any remaining organics, followed by washing of hydrochloric acid to remove carbonates. The remaining phytoliths were dried and weighed.

4.4.4 Micromorphology

Twelve oriented blocks of sediment were collected for micromorphological analysis (see Figure 4.3). Samples were impregnated with resin and ground into 5 x 7 cm petrographic thin sections to a standard thickness of 30 µm at The Australian National University. The thin sections were analysed by one of the authors (SM) at the University of Tubingen Institute for Archaeological Sciences using petrographic and stereomicroscopes equipped with plane-polarized, cross-polarized, reflected and oblique incident light (OIL), as well as darkfield illumination and blue light fluorescence. Descriptive criteria followed Stoops (2003).

4.5 Results

The magnetic susceptibility data reveal a strong correlation with the archaeological remains and stratigraphic units in the GS1 sedimentary sequence (Figure 4.4). In general, the susceptibility values rise at the position in the sequence where stone artefacts first occur (i.e. the lower-central portion of SU6), and both susceptibility and χfd remain consistently higher thank those found in the lower basal units. Values are highest in the upper portion of the sequence or in SUs 3–1. Samples are only weakly magnetic in the culturally sterile layers or the basal units of lower SU6, SU7 and SU8. As shown in Figure 4.4, a positive correlation between susceptibility and other parameters including stone artefacts (includes ochre), wood charcoal, LOI, phytoliths and phosphorous also exists.

Mineralogical transformations from the high temperature tests were present in SUs 3–1 and the upper portion of SU4 (Figure 5a–c). The presence of carbon (e.g. charcoal) or other carbon-rich organic material is likely the reason for these mineralogical transformations (see Lowe et al. in review). Common Fe-bearing soils minerals like goethite and hematite can be transformed to more strongly magnetic phases like magnetite and maghemite when this material is added to the soil and heated (Hanesch et al. 2006). Both charcoal and LOI% are also higher in SU1, SU2, SU3 and the upper portion of SU4. Alternatively, SU6, SU7 and SU8 had lower concentrations of carbon-rich material and thus no mineral transformations (see Figure 4.5b). Low temperature measurements also indicated some similarities and differences between the stratigraphic units. The Verwey transition is observed on the cooling leg for all samples under 115 K (Figure 4.5d–f) as well as on the warming leg, indicating that magnetite is present in the deposits. Low temperature tests revealed that goethite was also present. Samples in SUs 3–1 revealed evidence of hematite and ilmenite (Figure 4.5d), while samples in the middle of the sequence showed only magnetite, goethite and nano-hematite (Figure 5e). Fine-grained enhancement of magnetite mixed with goethite and hematite are common in soil forming minerals, yet their relative concentration within each component differs in each of GS1's samples indicating that they are not natural environmental processes but are instead modifications of anthropogenic burning (see Lowe et al. in review).

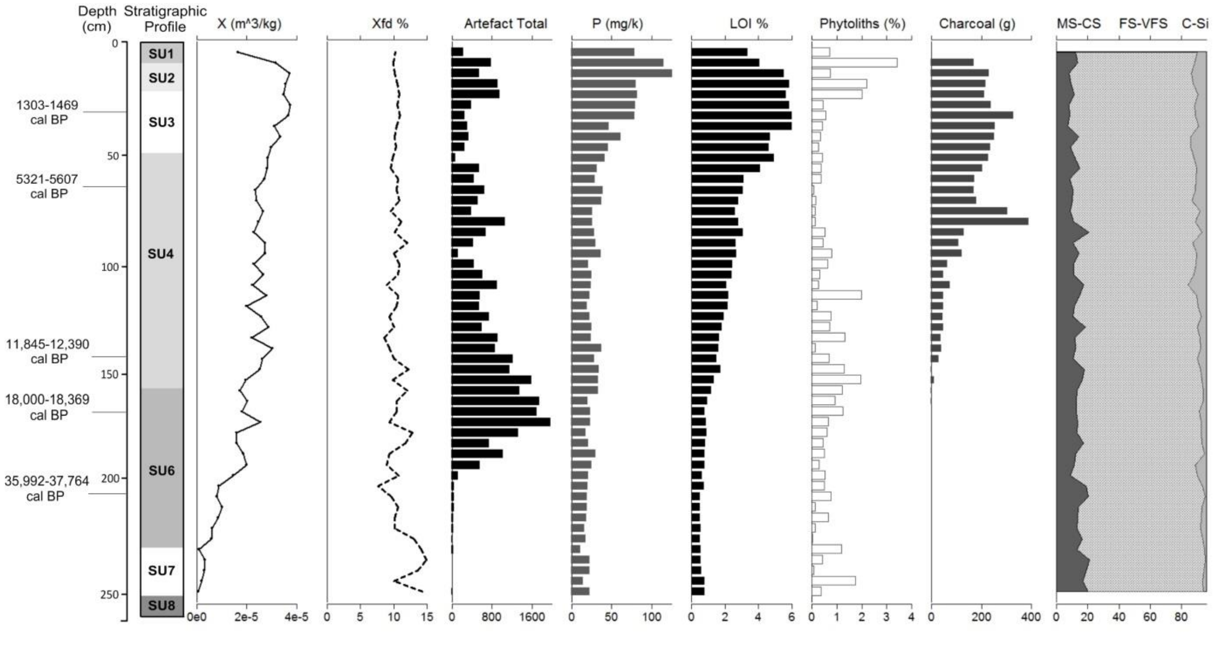

Figure 4.4 **Profile of low-field magnetic susceptibility and frequency dependence for Squares C1. Stratigraphic profile, stone artefact total, phosphorus, loss on ignition, phytolith, wood charcoal and particle size data are also provided. Laboratory numbers for radiocarbon from top to bottom: ANU-2625, Wk-33293, Wk-33296, Wk-33295, OZM094. MS = Medium Sand, CS = Coarse Sand, FS = Fine Sand, VFS = Very Fine Sand, C = Clay, Si = Silt.**

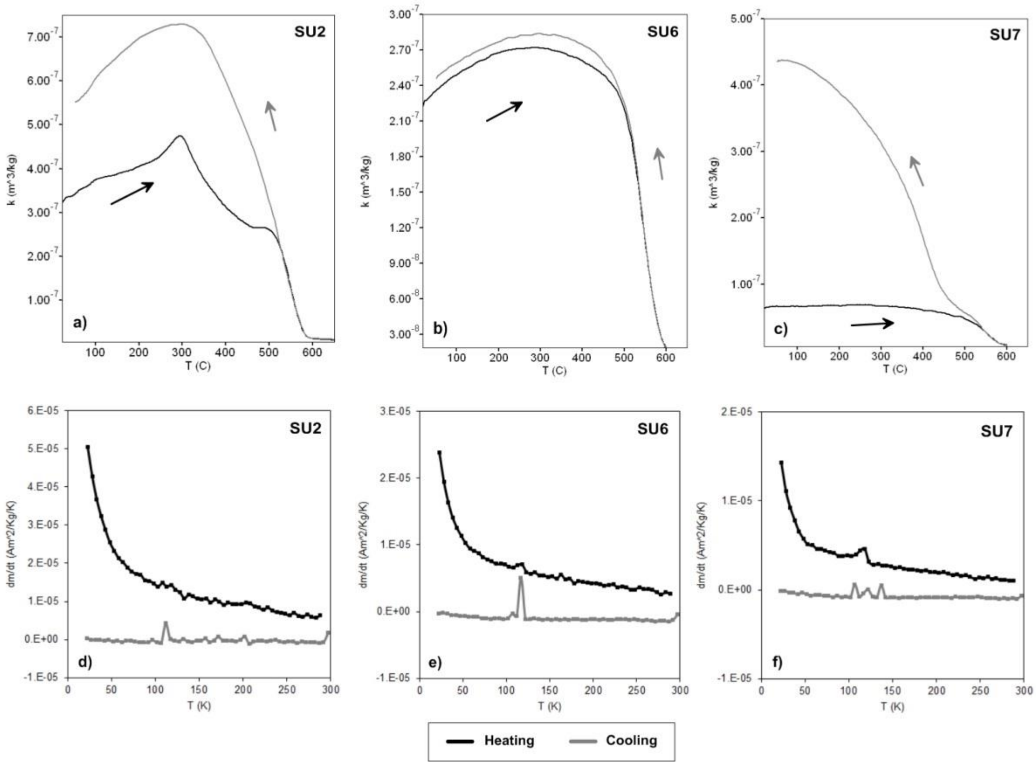

Figure 4.5 **High temperature (Curie point) curves on selected samples of (a) irreversible curves and the inversion of a new magnetic mineral, (b) reversible curves with only a minor amount of susceptibility created and (d) extremely irreversible curves and the inversion of a large amount of magnetic material. Low temperature derivative plots on selected samples confirm the presence of magnetite(e-f).**

The uppermost SUs, 3–1, have the highest concentrations of P and LOI, the values for which both decrease with depth and are strongly correlated (Table 4.3 and Figure 4.4). Magnetic susceptibility values and wood charcoal quantities were also higher in these units. Wood charcoal decreased significantly in the lower levels of SU4 and only a few fragments were preserved in SU6 (sees Figure 4.4). Phytoliths were present throughout the sequence, in greatest abundance in SUs 1 and 2, yet surprisingly large quantities in SU6 (after the arrival of people) and in lower SU4. In upper SU4 and SU3 phytolith abundances were extremely limited. A light density of stone artefacts first appears in the mid-lower portion of SU6. They become more abundant in upper SU6 and throughout SU4, before declining in abundance in SU3 and then rising again in SU2.

Particle size analyses reveal the GS1 deposits are dominated by fine to very fine sand-sized grains (70–80%), with small percentages of silt- and clay-sized material (≥ 10%) and medium- to coarse sand-sized material (5–15%) (Figure 4.4; see also Keys 2009). Silts and clays are more common in the upper portion of the sequence, decreasing slightly around 120 cm or below (i.e. mid-SU4). In turn, medium to coarse sands are less common near the surface of the sequence and increased slightly with depth. Most sediments are poorly sorted, though tend to be more moderately sorted in the upper three SUs, and contain a mix of both subangular and subrounded particles.

Table 4.3 Correlations between LOI (X) and Pav (Y).

SQUARE	LINE OF BEST FIT	R^2	*PEARSON'S r*
C1	1460.7x + 5.4266	0.7996	0.8942
B1	2077.4x + 1.2543	0.6502	0.8063
D1	2180.1x - 17.304	0.9167	0.9574
D0	3400.6x - 34.182	0.9181	0.9582
B0	2215.1x - 27.109	0.6556	0.8097

In thin section, the GS1 sediments are dominated by sand-sized materials, with quartz being the most abundant mineral (see Figure 4.6a). Sand-sized fragments of accessory silicates of sedimentary, metamorphic and igneous origin include microcrystalline quartz, mica and hornblende, along with opaque grains and mineral cements (see Figure 6a–c). Coarser materials include gravel-sized fragments of sandstone and quartzite. Silt- and clay-sized materials are primarily present as coatings and bridges between quartz grains, although they also form rounded, sand-sized aggregates. Primary depositional fabrics, such as graded bedding or laminations are generally absent, and structural development is low throughout the entire sequence, with most samples exhibiting a massive structure. Anthropogenic materials seen in thin section include gravel- to silt-sized, rounded charcoal fragments, as well as rare fragments of ochre and fragments of non-local quartzite. Ash and bone fragments were not documented in any of the micromorphology samples. Post-depositional features include tubular domains interpreted as infilled burrows, channel and chamber voids, fine sedimentary cappings on top of sand- and gravel-sized materials, compound grain coatings, and gravel-sized aggregates of sediment composed of sand-sized materials cemented with silt and clay. The vertical and lateral variation of primary geogenic and anthropogenic materials, structure and porosity, and post-depositional features are described in more detail below.

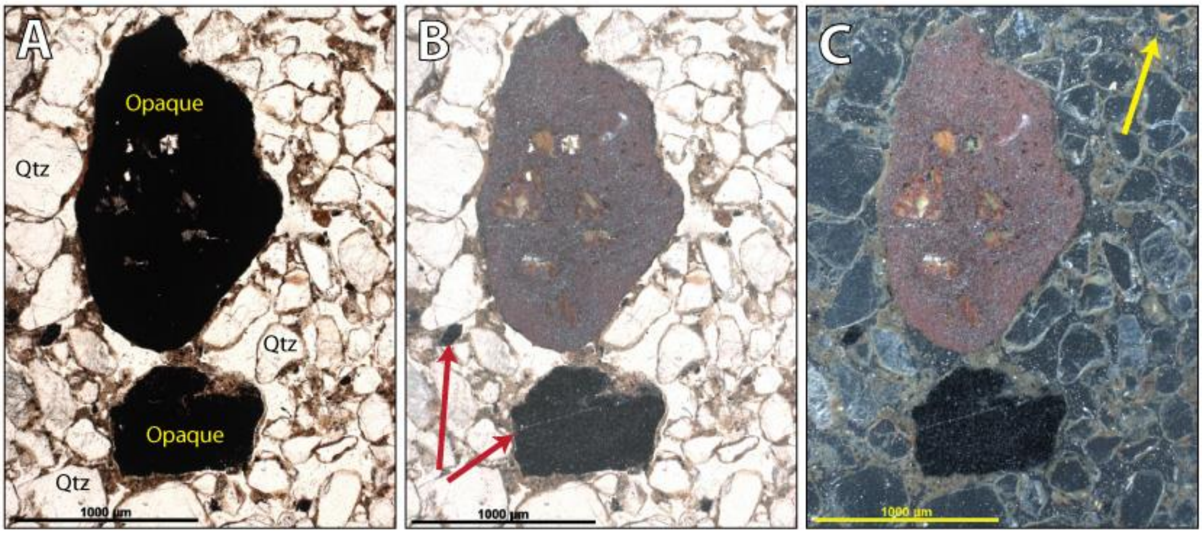

Figure 4.6 **The main geogenic sedimentary components as well as possible anthropogenic materials were identified in thin section. (a) A sample from SU4 contains abundant sand-sized grains of quartz (Qtz) coated and capped with fine sediment. Packing voids are present between the grains. Two coarse opaque materials are present in the centre of the field of view. PPL. (b) Opaque materials were identified using OIL. The lower of the two coarse materials, as well as smaller grains remain black under OIL (arrows). These materials are charcoal. Many fragments of charcoal visible in the thin sections also exhibit preserved cellular structure. The size and degree of rounding of charcoal fragments is variable throughout the sequence and likely relates to mechanical weathering processes, such as bioturbation and trampling. OIL, PPL. (c) The two upper opaque materials is strongly red to red-black under OIL. Internal variations in colour are due to the presence of weathered mineral inclusions within the material (likely hematite-rich ochre). Iron is also present within the quartz grain coatings (arrow). Other iron-bearing phases vary in colour in OIL. For example, goethite is yellow orange. The type and distribution of iron-bearing minerals was observed in the GS1 micromorphology samples and compared to the result of the magnetic measurements (see Discussion). OIL.**

The SU7 and SU6 deposits are characterised by a massive grading to locally spongy microstructure composed of sand- and silt-sized grains of quartz separated by packing voids (see Figure 4.6). The quartz grains within the matrix exhibit discontinuous thin coatings of clay-sized material. Gravel-sized aggregates containing sand-sized quartz grains, silt and clay are also present. The fine sediment in the aggregates range in colour and texture from red, moderately limpid clay, to yellow, limpid clay microlaminated with quartz silt. The outer edges of the aggregates contain increased abundance of yellow clay and silt-sized inclusions. Reflectance under OIL indicates that the red clay is rich in iron. Relative to the surrounding matrix, the aggregates contain sand-sized materials that exhibit a higher degree of textural sorting; accessory minerals such as biotite are also present.

Although two micromorphology samples were collected across the boundary between SU7 and SU6, a discrete contact between them is not recognisable in thin section. Relative to SU7, SU6 is more porous due to the presence of channel voids, and contains a higher abundance of silt- and clay-sized materials coating and bridging between the spaces of the quartz grains within the matrix

(Figure 4.7b, III), as well as a lower abundance of sedimentary aggregates. Weak laminations of coarse sand grains are present in SU6; however, this primary fabric is disrupted by the presence of infilled burrows (Figure 4.7b, II). Sand-sized grains, and one gravel-sized fragment of microcrystalline hematite are present in the SU7 and SU6 samples. The former are present as inclusions within sandstone fragments, which suggests that some types of hematite are naturally present in the GS1 deposits. Anthropogenic materials are absent from both SU7 and lower portion of SU6.

SU6a is characterised by sand-sized grains of quartz that exhibit thin, discontinuous coatings of clay. Some coatings exhibit internal stratification, with interior layers of iron-rich red clay overlain by brownish clay (Figure 4.8). The structure of this unit is massive, with packing voids between grains. Charcoal fragments are present, but are very rare. The majority of fine and coarse opaque materials are microcrystalline hematite and possible goethite. A fragment of material composed of sand-sized grains of quartz in a matrix of opaque material of mixed composition may be ochre (Figure 4.8). Tubular domains (mm- to cm-scale) exhibiting slight textural differences relative to the surrounding sediment are likely infilled insect burrows.

As in other units, the sedimentary matrix of SU4 is dominated by sand-sized grains of quartz with an overall massive structure punctuated by occasional channel voids. The sand grains are typically coated with yellowish brown clay mixed with charcoal, although multi-component coatings containing an interior layer of iron-rich red clay are also present. The overall fabric of the unit is consistent with infilled channel voids. Charcoal abundance is variable though most abundant at the top of the SU4 (Figure 4.9), with fragments ranging from angular, gravel-sized pieces, to well-rounded fragments of sand-size, as well as silt-sized fragments within quartz grain coatings. The coarse inclusions in this unit, which include gravel-sized fragments of charcoal, exhibit cappings of fine sediment on their upper surfaces. These cappings contain yellowish brown clay and silt-sized fragments of charcoal (see Figure 4.9b).

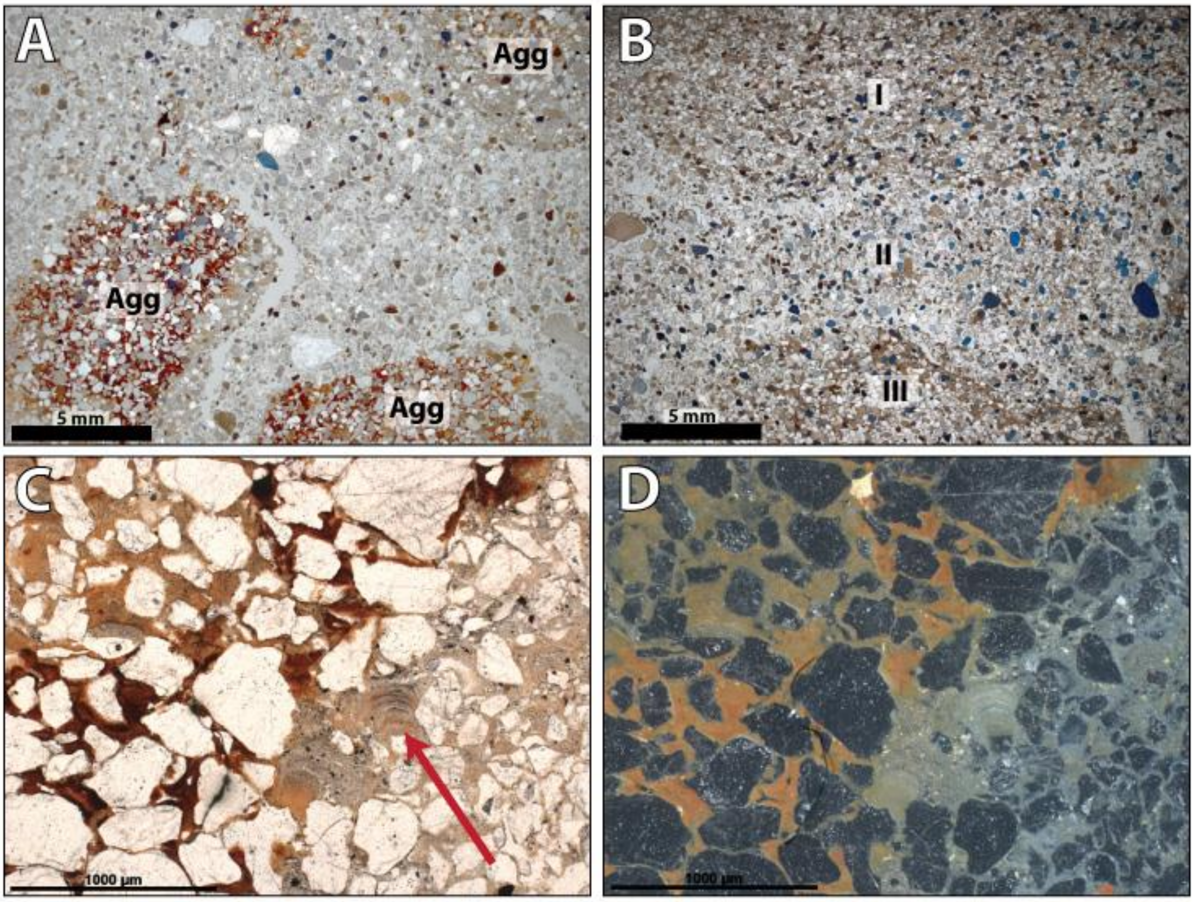

Figure 4.7 **The basal two units are characterised from the overlying sediment by reddish colour and lack of anthropogenic materials. (a) SU7 contains aggregates (Agg) of sand-sized quartz cemented with multiple types of fine material. Circular polarized light. (b) One sample from SU6 contains textural domains related to primary deposition and secondary processes. Weak laminations are present in the upper part of the image (I). These laminations are indicative of primary deposition or localised reworking by water. The base of the image contains sand-sized grains of quartz that are partially coated and capped with clay (III). The middle area (II) is more porous and contains less abundant fine material. Its tubular morphology is indicative of an infilled insect burrow. Circular polarized light. (c) The aggregates in SU7 contain fine materials that vary in colour and texture. The interior regions of the aggregates contain red clay overlain by yellowish clay. The exterior zones contain yellow clay mixed with quartz silt. Irregular edges and crescentric infillings (arrow) indicate that the aggregates have been rotated and transported from their original place of formation. PPL. (d) Under OIL, the red clay is rich in iron. Same view as (c), OIL.**

SU3 contains abundant sand-sized, well-rounded fragments of charcoal in a matrix of loose quartzitic sand. The sand grains are coated in fine sediment, with multicomponent coatings comprised of interior layers of yellowish brown clay and exterior layers composed of silt-sized fragments of charcoal and degraded organic material. Aggregates of sand grains cemented with reddish clay are also present. Fragments of degraded organic material are associated with secondary iron oxides. The overall fabric of the sample, like those from SU4, is consistent with infilled channel voids.

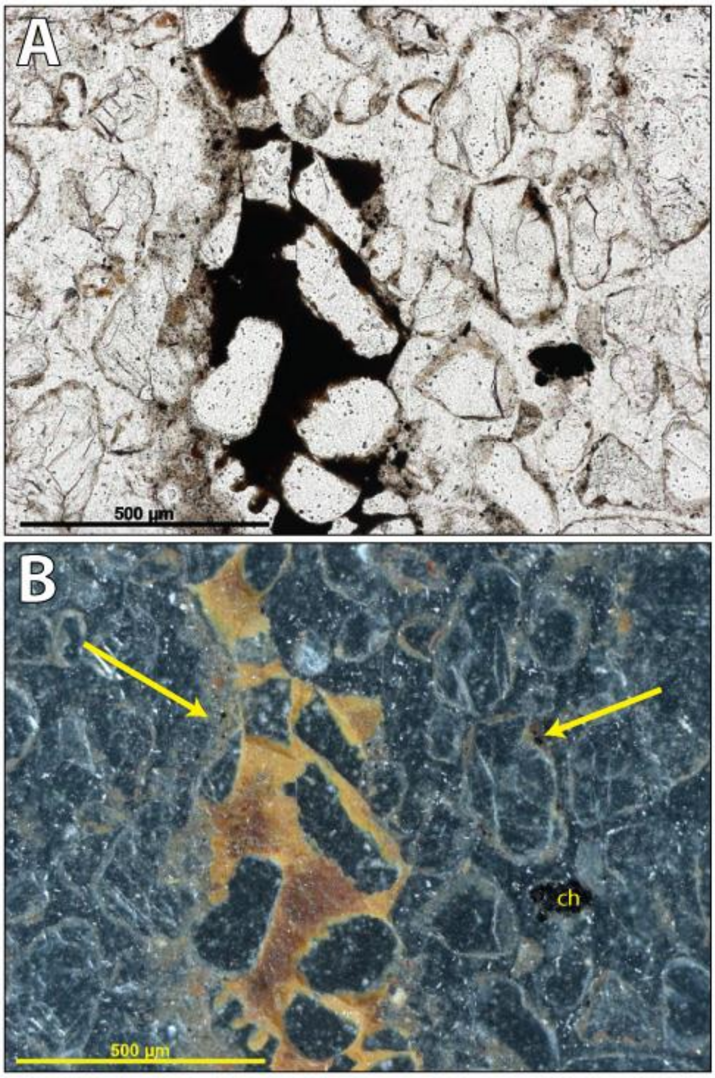

Figure 4.8 **Anthropogenic materials are present in low abundances in SU6a. (a) An angular fragment of possible ochre is present in a matrix of sand. PPL. (b) Under OIL, the iron-rich cement is visible. Silt-sized grains of iron-rich material, as well as charcoal fragments are present in fine sediments coating both quartz grains and the ochre fragment (arrows). A sand-sized fragment of charcoal is also visible (ch).**

The sample from SU2 contains intact sediment at its base, as well as an upper disturbed area that may contain sediment sourced from SU1. The basal portion of the sample is very similar to the sediment that is present in SU3, with coated, sand-sized grains of quartz, and abundant fragments of charcoal, particularly within the sand fraction. Fragments of organic material and faecal pellets of insects are also present. The upper portion of the sample is highly porous and contains abundant fragments of fresh to partially-humified organic material.

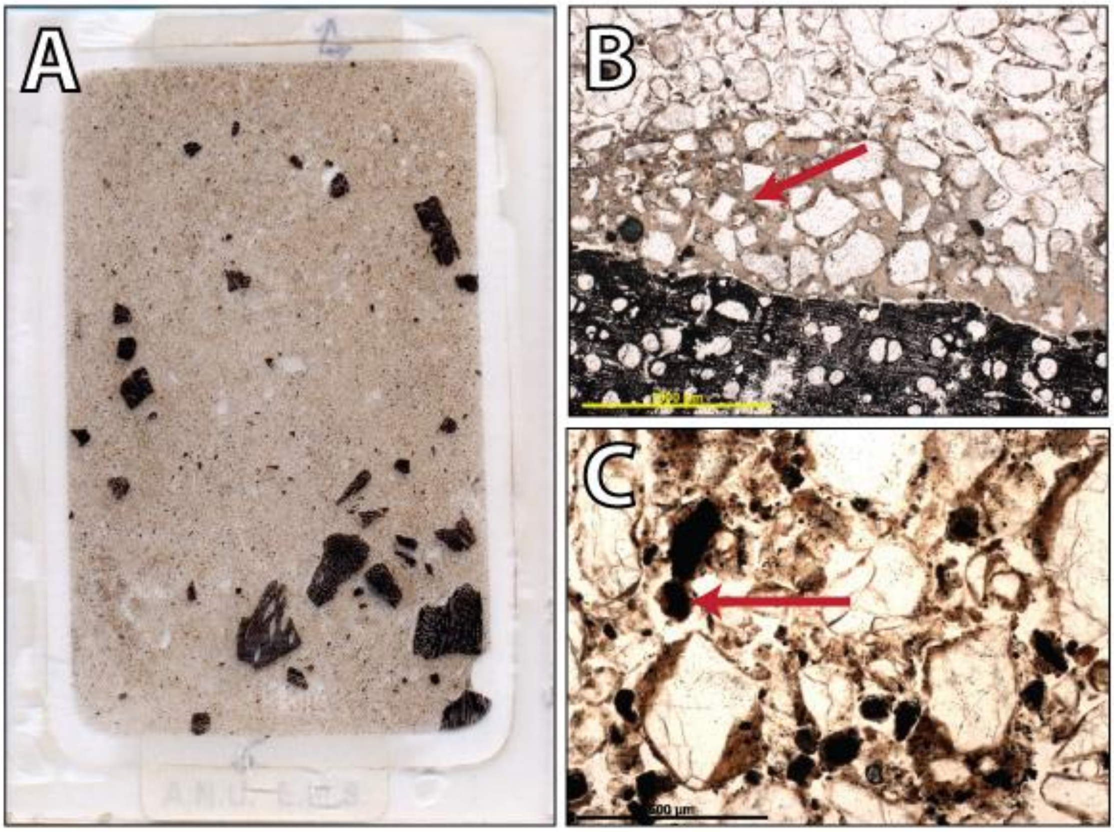

Figure 4.9 **Samples from SU4 contain variable amounts of charcoal distributed within the matrix, as well as within textural pedofeatures. (a) An incident light scan of a thin section from SU4 illustrates the abundant subangular fragments of charcoal in the gravel-sized particle fraction. The dark colour of the matrix is due partially to the presence of smaller fragments of charcoal. 5 x 7 cm. (b) Coarse materials in this unit exhibit cappings of fine sediment. Here, a fragment of charcoal is capped with sand embedded in a mixture of silt and brown clay. Crescentric infillings (arrow), and inclusions of charcoal are present within the cappings. PPL. (c) In the uppermost samples from the unit, as well as in overlying SU3, charcoal is abundant in the sand-sized particle fraction. Here, all opaque materials except one (arrow) are charcoal. Silt-sized fragments of charcoal are mixed with brown clay within the sand grain coatings. PPL.**

4.6 Discussion

4.6.1 Site Formation Processes

The GS1 site is a small sandstone overhang that has formed through the process of cavernous weathering known as tafoni. Accumulation of the sedimentary deposits in the site resulted from both natural and cultural processes. There is little evidence of soil horizonation throughout the sequence and the upper stratigraphic unit’s organic materials show progressive decomposition with depth, consistent with only very weak soil formation at the ground surface. Buried surfaces and lag deposits are not present. The majority of sediment deposited at GS1 is geogenic in origin, and likely sourced from roof fall and weathering of the local sandstone bedrock as evidenced by the granular disintegration and overall composition, texture and fabric of the sediments in thin section. Microcrystalline hematite present within the sandstone is also apparent within the sand- and silt-sized particle fractions of the sedimentary deposits. Several of the fine coatings visible on grains in thin section contain clays that are rich in iron, as evidenced by their strong red colours. Iron is also present as sand-sized fragments of ochre. Of these materials, the silt-sized particles of microcrystalline hematite and the reddish clays appear to be most mobile throughout the sequence, as they are frequent components of grain coatings and cappings in the lower units.

Lesser inputs of anthropogenic materials, including charcoal, stone artefacts and ground ochre are present from mid-SU6 and above, though absent in SU8 and SU7, and the lower portion of SU6. Despite the geogenic nature of the majority of the sediment, in addition to the artefactual remains there is evidence for significant human modification of the deposits, primarily via the magnetic data. The rise in magnetic susceptibility and the distinctive temperature data are consistent with human occupation that involved both fires and the incorporation of organic carbon. Low values of charcoal and stone artefacts where magnetic susceptibility is low, indicates a low absence of people. When humans begin to utilise the site fully, we see an increase in all three indicating that site use was more intensive and involved activities such as cooking and stone tool making.

Within SU4, when it first appears preserved in the sequence, the overall abundance of charcoal, its distribution across various particle size classes, and the degree of rounding of individual fragments varies, with the coarsest and most abundant charcoal in the upper part of this SU. Above this, rounded, sand-sized fragments of charcoal are abundant in SU3 and SU2, where post-depositional disturbance is more visible, particularly in thin section. Discrete layers or lenses of charcoal are absent from the entire sequence, as are other hearth components that can be readily identified in thin section – when present – such as layers of ash or basal zones of heat-altered (reddened) substrate (c.f. Mentzer 2013). Other markers of burning within the shelter, such as burned bones, or heated rock fragments, were not recovered. The absence of anthropogenic sedimentary features in GS1, associated with burning or otherwise, is likely due to dissolution combined with syn- or post-depositional mixing by humans (e.g. scuffing and trampling), insects and larger fauna. These processes resulted in mechanical abrasion and lateral reworking of coarse charcoal fragments, and resulted also in fine comminuted charcoal especially in SUs 1–4.

The water table in the study area is too low for groundwater to be significant at the site and no redoximorphic features were present (Holliday 2004; Schiffer 1987). Yet, although wetting of the deposit is not occurring today, with excavated sediments between the shelter wall and drip-line remaining dry even during extreme rainfall events (as were experienced at the end of the 2008 field season), the micromorphological evidence indicates that water has played an important role in shaping the GS1 deposits, at least in the pre-Holocene units. As evidenced in thin section, fine material has translocated downward through the sequence, forming thin cappings and bridges on sand grains. Thicker silty clay cappings on gravel-sized materials, especially in the lower SUs are also evident in thin section, while crescentric coatings within some cappings (see Figure 4.9b) indicate definitively that some of the translocation was associated with the movement of water through the sequence. Coatings composed of clay mixed with silt-sized fragments of quartz and iron-bearing opaque minerals, and aluminium sesquioxides are present in the lowest units, in addition to gradual disintegration with depth of other material into smaller particles (as is the case for the charcoal). Coatings and features such as these are often associated with increased precipitation (Birkeland 1999). In the upper units, coatings contain only fragments of charcoal and clay. The absence of distinct buried surfaces or anthropogenic features in the deposit also suggests that weathering process (dissolution) had an effect on the preservation. This is additionally confirmed with the level of post-depositional mixing by humans (e.g. scuffing and trampling) and insect bioturbation as revealed in the micromorphology.

The rate of sedimentation at GS1 varied considerably through time, with low sedimentation rates during the late Pleistocene and into the LGM. After the LGM through to the mid-Holocene (SU4), sedimentation rates increased significantly (Figure 4.10). An increase in sedimentation during the Holocene is a phenomenon that has been observed at other Australian rockshelter sites, and is argued to be linked to increases in the intensity of human occupation and site use (Hughes 1978) or increased firing in the locale, which resulted in more mobile sediments (Sullivan and Hughes 1983). However at GS1, the incorporation of a greater abundance of gravel and cobble sized sandstone fragments falling from the top of the outcrop during the early Holocene apparently accounts for most of this increase in sedimentation. Why this should be the case is unclear, but may perhaps be related to an increase in precipitation at this time or jointing of the sandstone escarpment. The rates of sedimentation fall slightly after the mid-Holocene, in those units represented by SUs 3–1, but are still much greater than those experienced in the LGM and pre-LGM levels.

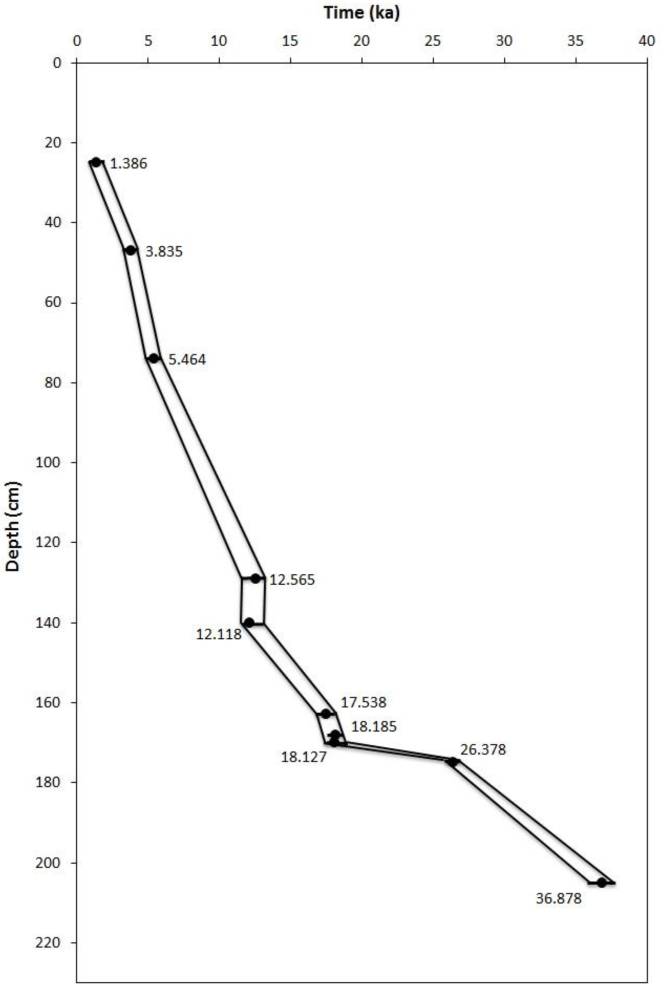

Figure 4.10 Age-depth curve. There is relatively fast accumulation of sediments in the early part of the record to about 37 ka. Accumulation rates slow down between ca 26 and 18 ka and there is more rapid sedimentation after 18 ka. The rapid post 18 ka rates are amplified by the incorporation of rock fall events from the roof of the shelter and this may also contribute to the high rates at the base.

4.6.2 Archaeology

The depositional sequence in GS1 commenced sometime prior to 40,000 years ago and was followed by the appearance of stone artefacts indicating utilisation by people around 36,000–37,700 cal. BP. After humans started inhabiting the site, modifications to the natural sedimentary sequence commenced, with a strongly positive correlation between the initial incorporation of discarded artefacts and an increase in magnetic susceptibility.

Stone artefacts, ground ochre and wood charcoal are present throughout the sequence from mid-SU6 and above, with no indication for a cultural or temporal hiatus such as are apparent in many other Pleistocene sites in Sahul (cf. David et al. 1997; O’Connor et al. 2003). Based on the chronological, archaeological and geoarchaeological data, it appears that the site was continually occupied from ca 38,000 cal. BP through the LGM and into recent times. The presence of stone artefacts indicates that tool manufacture using locally available quartzite, quartz, rhyolite and chert, with some rare appearances of basalt, crystal quartz and chalcedony was occurring. Quartzite, rhyolite and silcrete began disappearing from the lithic repertoire in the mid-Holocene, suggesting possibly a reorganisation of people in the landscape at that time. While it is difficult to interpret the ground ochre as an indicator for the production of rock art, it is possible the ochre was being ground for some other purpose (such as body art or decoration of ceremonial or secular portable artefacts). Without absolute dating of the rock art, the intended use of the ground ochre will remain speculative. As is the case with the stone artefact assemblage (see Wallis et al. unpub data), there are also important changes in the Holocene portion of the sequence with regards to the ochre; not only does this material decline in abundance, but the average size of ochre fragments also decreases to approximately half of what they were in the Pleistocene.

While no bone, non-charred plant remains (e.g. seeds) or discrete hearths were observed in the excavations or in thin-section, the mineral magnetic and charcoal data indicate that the occupants were using fire in the site. The absence of this material is due both to preservation (dissolution), bioturbation and human trampling. Since hearths burn for longer durations and at higher temperatures, and require a significant amount of wood fuel than do natural fires, the increases in magnetic enhancement with the onset of stone artefacts, the distinctive temperature tests and presence of charcoal are consistent with anthropogenic burning rather than natural bushfires (see Lowe et al. in review).

The organics and P values are also good indicators for human occupation at GS1, and both correlate strongly with the artefactual and magnetic susceptibility data. Organic and available P values double after the LGM through to the mid-Holocene and continue to rise more markedly in the uppermost units. While organic matter can decrease rapidly with depth in a sequence due to a lack of biota living in the upper soil horizons (Bettis 1988; Holliday 1988), the dissolution combined with syn- or post-depositional mixing by humans, insects and larger fauna may have also had a large effect on this reduction in the late LGM and early Holocene deposits.

4.6.3 Climate-Human Occupation Inferences

Figure 4.11 displays the temporally and volumetrically adjusted quantities of Square C1 artefacts plotted against the summer insolation curve at 15°S (from Berger and Loutre 1991) for the last 40,000 years. If we assume that the absence of artefacts prior to 38,000 years ago reflects an absence of people in the local area at this time, there is a first order similarity between the curves for summer insolation and the accumulation of artefacts at the site, with a peak of artefacts at the

LGM (22,000–18,000 cal. BP) and generally high values between 30,000 and 15,000 cal. BP. We note that this observation needs to be treated with some caution because the sediment deposition rates are very low, especially immediately prior to and in the early parts of the LGM (see Figure 10). However, the artefact curve is normalised to time, so the broad peak across the 30,000–15,000 cal. BP period is real. This result is unexpected because the LGM is argued to be a time of aridity in northern Australia (e.g. Reeves et al. 2013) and is generally regarded as a period when interior sites are abandoned or at least activity focusses on well watered refugia (Hiscock 1998; Hiscock and Wallis 2005; Veth 1989; Williams et al. 2013).

Occupations of GS1 as well as other sites in this region depend on the reliability of rainfall. In northern Australia almost all the rainfall occurs between December and May and is derived from the Australian summer monsoon or cyclones, or both (Webster and Stretton 1978). It is argued that the strength of the northern Australian monsoon relates to either the east Asian winter monsoon (e.g. Shaiu et al. 2011) and/or the Indian summer monsoon (e.g. Mohtadi et al. 2011). However, while interhemispheric climate teleconnections may be important, the local driver of monsoon intensity is summer insolation in the Indonesia-North Australia region (e.g. Wrywoll et al. 2012). There is a strong summer insolation maximum centered on the LGM and, all other factors being equal, the monsoon should be active in northern Australia at the LGM (though see Spooner et al. 2005).

Another factor does come into play. When global sea levels fall during the ice ages due to the trapping of water in the Laurentide and Fenno-Scandian ice sheets, much of the broad shelf along the northern Australian coast, and many of the shallow seas in the Indonesian Aarchipelago, become exposed land. This removes much of the evaporative pan that drives the monsoon and cyclogenesis in the Gulf of Carpentaria and the Sahel Shelf. It should be noted that existing reconstructions from northern Australia, which indicate dry conditions and no monsoon at the LGM, are based from sites that would derive most of their moisture from the exposed Sahel Shelf area (e.g. Reeves et al. 2008). There is a second source of monsoon moisture: the Coral Sea. These waters off north Queensland remain relatively warm through the LGM (e.g. Bostock et al. 2013) and, while there is an increased exposure of shelf along the northeast Queensland coast, it is minor compared to the marine regression in northwestern Australia and the Gulf of Carpentaria. In short, the GS1 site is located in a region where monsoonal moisture comes both from the Gulf of Carpentaria and from the Coral Sea. Moisture from the Coral Sea also penetrates inland during the winter (dry) season due to onshore southeast trade winds. Most of this moisture is intercepted along the Great Dividing Range but some penetrates inland and rainfall on the divide feeds the headwaters of the local river systems. The presence of people at GS1 through the LGM is strongly suggestive that this time period may not have been as dry in this area as was the case further west or south.

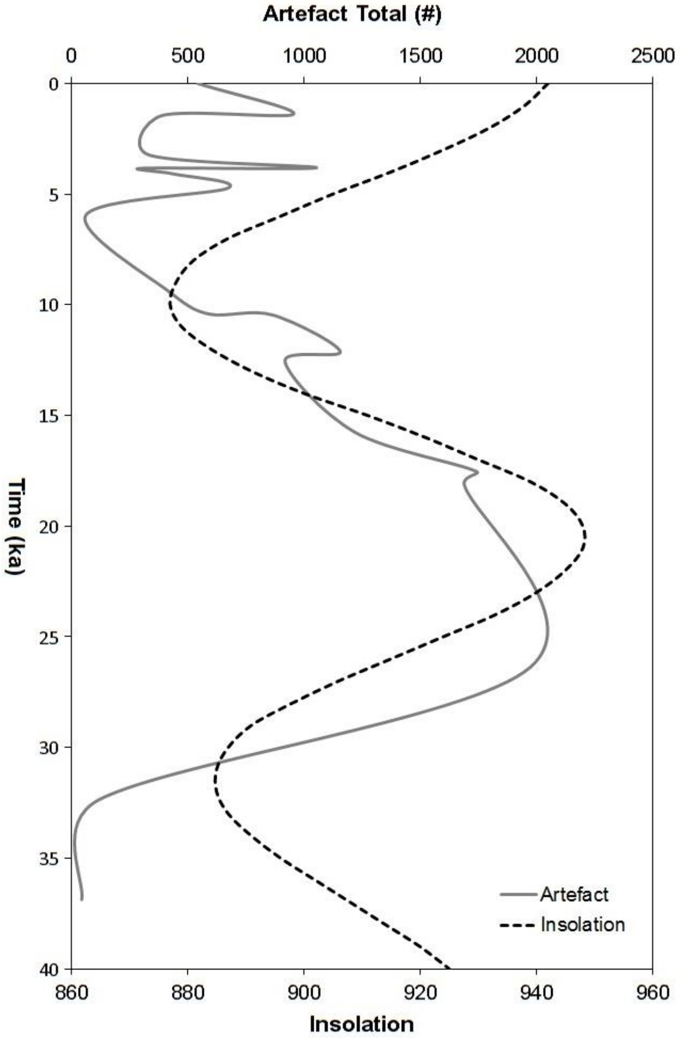

Figure 4.11 **A comparison between the accumulation rates (by count) of stone tools and summer insolation at 15°S (from Berger and Loutre 1991). The former is a crude proxy for human activity at the site, while summer insolation is the first order control on the strength of the local monsoon. The effectiveness of the local monsoon will control the availability of water in this region. We postulate that there is a causal relationship between available water and human activity at the site.**

This does not mean that the monsoon was as strong as the present day. The EP is a function of both precipitation and evapo-transpiration. There is evidence that the southern half of Australia cooled by between 8–10°C at the LGM (e.g. Galloway 1965; Miller et al. 1997) and there is also evidence that the winter westerlies penetrated at least as far north as they do today (e.g. Petherick et al. 2009). It is assumed, but not demonstrated that cooling was less in the northern part of the continent but even relatively modest cooling of 4–5°C would significantly reduce evaporation and would lead to a more positive moisture balance even under somewhat reduced precipitation. In summary, for sites that have access to east coast moisture sources, either directly through precipitation or through the flow of rivers into the area, the insolation maximum at the LGM may have presented new opportunities for occupation as well as a well-watered refuge for this interior corridor site.

The next obvious question is why there is no equivalent peak in occupation in the late Holocene when insolation values are also high. It has already been noted that ENSO activity becomes more persistent in the late Holocene (e.g. Shulmeister and Lees 1995), which affected the reliability of precipitation in the last few thousand years. With higher temperatures than prevailed during the LGM, Holocene evapotranspiration rates would have been significantly higher and the impact of intermittent dry years much more severe than during the LGM.

People are resilient and take advantages of environmental opportunities. Several other areas in Australia show enhanced occupation during the LGM and these are button-grass moorland sites in Tasmania (Cosgrove 1999) or the Aru Islands, in Western Australia (O’Connor and Veth 2006). In this case, the local conditions were harsh (with glaciation nearby) but human presence was supported by rich game reserves and available water. Though there is no direct evidence for hunting, enhanced or otherwise, at the GS1 site owing to the lack of bone preservation, more reliable water supplies would have made both game and plant resources more widely available and supported the human presence through the LGM.

4.7 Conclusion

Results from this study demonstrate the value in integrating magnetic susceptibility and micromorphology data with other archaeological analyses as means of understanding more fully the nature and persistence of human occupation in an archaeological rockshelter, as well as the stratigraphic record of an interior Pleistocene site. Presently, only a few archaeological studies have used both of these methods jointly; in Australia, while individually such studies are occasionally undertaken, concurrent studies are extremely rare. The absence of discrete hearths in the GS1 deposits opened up the possibility that the charcoal present may have been the result of natural bush-fires, and the mineralogical and magnetic susceptibility data indicates that the majority of the burning within GS1 was anthropogenic in origin. Micromorphological studies confirmed the presence of microcharcoal in thin section, even in the lower cultural units where macroscopic evidence of charcoal or burning was entirely absent. While the micromorphology identified the presence of iron-bearing minerals, particularly microcrystalline hematite, the high and low temperature magnetic susceptibility tests were necessary to identify the presence of other fine-grained minerals including magnetite, goethite and ilmenite. And while neither the magnetic neither susceptibility nor particle size data showed the distribution of these magnetic minerals, or revealed whether they had been impacted by post-depositional processes, this information was apparent from the micromorphology data. As such, the incorporation of both magnetic susceptibility and micromorphology was crucial to understanding the site formation processes.

Secondly, this study revealed that initial sediment deposition at the site comprised solely local input mechanisms related to the natural weathering of the sandstone bedrock and roof fall. Around 38,000 cal. BP a new agent began to influence sedimentation in the site: people. Their presence was apparent not only from the stone artefacts they deposited, but from the increases in magnetic susceptibility caused by their intense burning of the sediments, apparent in the geophysical data despite the lack of preservation of associated macroscopic charcoal.

The presence of stone artefacts with associated radiocarbon dates up to and during the LGM indicates that this site was occupied through this period, thereby implying that water was at least locally available. This is despite the absence of any obvious permanent water source, such as is apparent at other sites occupied in northern Australia through the LGM, such as at Lawn Hill—water availability in the GS1 study area is reliant solely on summer rainfall events feeding the river systems and replenishing the aquifer that feeds localised small-scale springs. In addition, the micromorphological evidence demonstrates that, despite the absence of water acting on the deposits today, the Pleistocene units were affected by water as seen in the coatings present on grains. We therefore argue that the eastern Coral Sea monsoons would likely have remained active during the LGM, otherwise people could not realistically have continued to occupy the GS1 region. Rainfall availability also seemingly played an important role in how people responded to climatic changes, as strongly suggested by the offset of stone artefacts to the insolation curve. It is clear that, as climatic shifts occurred, GS1's occupants responded in a way that resulted in changes in the intensity of site use. Of course, the challenge remains in finding palaeoenvironmental proxies that will allow these propositions to be tested, a challenging task given the local landscape.

Neither the micromorphology and magnetic susceptibility displayed evidence of horizonation nor discrete boundaries between stratigraphic units, and neither were buried surfaces or breaks in occupation identified. Post-depositional mixing by humans and insects further resulted in the abrasion and lateral reworking of coarser material, such as charcoal, in the cultural units. Despite this, we do see robust vertical trends in all categories of remains in this site, indicating that the degree of mixing may be minimal. We suggest the geoarchaeological evidence demonstrates a shallow zone of disturbance had always been active at the contemporary ground surface; however, once further sediment accumulated, the disturbance effectively ceased and the deposits stabilised, preserving an intact sequence of human occupation. This suggests that, unless there is compelling stratigraphic evidence to indicate the survival of thin occupation lenses, excavation units finer than 5 cm in similar sandstone rockshelter contexts in northern Australia are unlikely to be of value.

In conclusion, people commenced utilising the GS1 site around 38,000 years ago, in a region that has been characterised as a potential corridor for early colonists moving southwards across the continent and into the arid interior. At this time, regional palaeoclimatic reconstructions suggest the region was similar, or more favourable than that present today. Moving forward in time, while the LGM had demonstrable effects on both the natural and cultural inputs to the site, it does not appear that people abandoned GS1 or the region, despite there being no obvious source of permanent water nearby. There is no evidence of culturally sterile sediments through the LGM, nor a lag deposit. The challenge is now for researchers to locate other sites of similar antiquity in the region to test our hypotheses.

Acknowledgments

We thank Kathryn Fitzsimmons in the Department of Human Evolution at the Max Planck Institute for Evolutionary Anthropology undertook the OSL dating, the results of which will be presented elsewhere. David Appleton in the School of Agriculture and Food Science at The University of Queensland carried out the processing of phosphorous samples and Josh Feinberg, Mike Jackson and Dario Bilardello from the Institute of Rock Magnetism, University of Minnesota assisted with the magnetic analysis. Stewart Fallon, Ben Keys, Xavier Carah, Claire St George, Chantal Wight, Lydia McKenzie and Ian Moffat have been involved with various other aspects of the research and are thanked for their contribution to the wider project. We also thank the Woolgar Valley Aboriginal Corporation for supporting this research, including for participating during fieldwork, and Flinders University, the Australian Institute of Nuclear Science and the Australian Institute of Aboriginal and Torres Strait Islander Studies for funding the research. K.M.L. was funded by the Institute of Rock Magnetism, University of Minnesota Visiting Research Fellowship and the University of Queensland, through an International Postgraduate Research Scholarship and Centennial Scholarship, and a Graduate School International Travel Award.

References

Ajas, A., P. Bertran, L. Lemée and A. Queffelec 2013 Stratigraphy and Palaeopedology of the Palaeolithic Cave Site of Combe-Saunière, Southwest France. *Geoarchaeology* 28:432–449.

Allen, J. and J. F. O'Connell 2003 The long and the short of it: Archaeological approaches to determining when humans first colonised Australia and New Guinea. *Australian Archaeology* 57, 5–19.

Allen, J. and J. F. O'Connell in press Both half right: Updating the evidence for dating first human arrivals in Sahul. *Australian Archaeology* 79:x–x.

Bailey, G. 2007 Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26:198–223.

Bettis, E. A. 1988 Pedogenesis in late Prehistoric Indian mounds, upper Mississippi valley. *Physical Geography* 9:263–279.

Berger, A. and M. F. Loutre 1991 Insolation values for the climate of the last 10 million years. *Quaternary Sciences Reviews* 10(4):297–317.

Birdsell, J. B. 1957 Some population problems involving Pleistocene man. *Cold Spring Harbor Symposia on Quantitative Biology* 22:47–70.

Birkeland, P. W. 1999 *Soils and Geomorphology*. New York: Oxford University Press.

Bostock, H. C., T. T. Barrows, L. Carter, Z. Chase, G. Cortese, G. B. Dunbar, M. Ellwood, B. Hayward, W. Howard, H. L. Neil, T. L. Noble, A. Macintosch, P. T. Moss, A. D. Moy, D. White, M. J. M. Williams, and L. K. Armand 2013 A review of the Australian-New Zealand sector of the Southern Ocean over the last 30 ka (Aus-INTIMATE project). *Quaternary Science Reviews* 74:35–57.

Bowdery, D. 1998 *Phytolith Analysis Applied to Pleistocene-Holocene Archaeological Sites in the Australian Arid Zone.* BAR International Monograph Series 695. Oxford: Hadrian Books.

Bowdler, S. 1977 The coastal colonisation of Australia. In J. Allen, J. Golson and R. Jones (eds), *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*, pp. 205–246. London: Academic Press.

Bowler, J. M., H. Johnston, J. M. Olley, J. R. Prescott, R. G. Roberts, W. Shawcross and N. A. Spooner 2003 New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421(6925):837–840.

Bowler, J. M. and D. M. Price 1998 Luminescence dates and stratigraphic analyses at Lake Mungo: Review and new perspectives. *Archaeology in Oceania* 33:156–168.

Bronk Ramsey, C., M. Dee, S. Lee, T. Nakagawa and R. Staff 2010 Developments in the calibration and modelling of radiocarbon dates. *Radiocarbon* 52(3):953–961.

Carah, X. 2010 *Corridors and Callitris: Examining the Changing Use of Environment, Through the Gledswood Shelter 1 Wood Charcoal Assemblade*. Unpublished Honour's Thesis, School of Social Science, The University of Queensland, St Lucia.

Cosgrove, R. 1999 Forty-two degrees south: The archaeology of late Pleistocene Tasmania. *Journal of World Prehistory* 13:357–402.

Dalan, R. A. and S. K. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13:3–36.

David, B., R. G. Roberts, J. Magee, J. Mialanes, C. Turney, M. Bird, C. White, K. L. Fifield and J. Tibby 2007 Sediment mixing at Nonda Rock: Investigations of stratigraphic integrity at an early archaeological site in northern Australia and implications for the human colonisation of the continent. *Journal of Quaternary Science* 22(5):449–479.

David, B., R. G. Roberts, C. Tuniz, R. Jones and J. Head 1997 New optical and radiocarbon dates from Ngarrabullgan Cave, a Pleistocene archaeological site in Australia: Implications for the comparability of time clocks and for the colonisation of Australia. *Antiquity* 71:183–188.

Davidson, I., S. A. Sutton and S. J. Gale 1993 The human occupation of Cuckadoo 1 Rockshelter, northwest Central Queensand. In M. A. Smith, M. Spriggs and B. Fankhauser (eds), *Sahul in Review: Pleistocene Archaeology in Australia, New Guinea and Island Melanesia*, pp. 164–172. Canberra: Department of Prehistory, Research School of Pacific and Asian Studies, The Australian National University.

Ellwood, B., F. B. Harrold, S. L. Benoist, P. Thacker, M. Otte, D. Bonjean, G. J. Long, A. M. Shahin, R. P. Hermann and F. Grandjean 2004 Magnetic susceptibility applied as an age-depth-climate relative dating technique using sediments from Scladina Cave, a late Pleistocene cave site in Belgium. *Journal of Archaeological Science* 31(3):283-293.

Ellwood, B. B., K. M. Petruso, F. B. Harrold and J. Schuldenrein 1997 High-resolution paleoclimatic trends for the Holocene identified using magnetic susceptibility data from archaeological excavations in caves. *Journal of Archaeological Science* 24:569–573.

Evans, M. E. and F. Heller 2003 *Environmental Magnetism: Principles and Applications of Enviromagnetics*. London: Academic Press.

Farrand, W. R. 2001 Sediments and stratigraphy in rockshelters and caves: A personal perspective on principles and pragmatics. *Geoarchaeology* 16:537–557.

Fassbinder, J. W. E., H. Stanjekt and H. Vali 1990 Occurrence of magnetic bacteria in soil. *Nature* 343(6254):161–163.

Fifield, L. K., M. I. Bird, C. S. M. Turney, P. A. Hausladen, G. M. Santos and M. L. di Tada 2001 Radiocarbon dating of the human occupaton of Australia prior to 40 ka BP – Success and pitfalls. *Radiocarbon* 43:1139–1145.

Galloway, R. W. 1965 Late Quaternary climates in Australia. *The Journal of Geology* 73:603–618.

Gifford-Gonzalez, D. P., D. B. Damrosch, D. R. Damrosch, J. Pryor and R. L. Thunen 1985 The third dimension in site structure: An experiment in trampling and vertical dispersal. *American Antiquity* 50:803–818.

Hanesch, M., H. Stanjek and N. Petersen 2006 Thermomagnetic measurements of soil iron minerals: The role of organic carbon. *Geophysical Journal International* 165:53–61.

Harrison, S. P. 1993 Late Quaternary lake-level changes and climates of Australia. *Quaternary Science Reviews* 12:211–231.

Herries, A. I. R. 2006 Archaeomagnetic evidence for climate change at Sibudu cave. *South African Humanities* 18:131–147.

Herries, A. I. R. and E. C. Fisher 2010 Multidimensional GIS modeling of magnetic mineralogy as a proxy for fire use and spatial patterning: Evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution* 59:306–320.

Hiscock, P. 1988 *Prehistoric Settlement Patterns and Artefact Manufacture at Lawn Hill, Northwest Queensland*. Unpublished PhD thesis, School of Social Science, The University of Queensland, St Lucia.

Hiscock, P. 2008 *Archaeology of Ancient Australia.* London: Routledge Taylor and Francis Group, London.

Hiscock, P. and L. A. Wallis 2005 Arid paradises or dangerous landscapes: A review of explanations for Paleolithic assemblage change in arid Australia and Africa. In P. Veth, M. Smith and P. Hiscock (eds), *Desert Peoples: Archaeological Perspectives,* pp. 58–77. Oxford: Blackwell.

Hogg, A. G., Q. Hua, P. G. Blackwell, M. Niu, C. E. Buck, T. P. Guilderson, T. J. Heaton, J. G. Palmer, P. J. Reimer, R. W. Reimer, C. S. M. Turney and S. R. H. Zimmerman 2013 SHCal13 Southern Hemisphere calibration, 0–50,000 years cal. BP. *Radiocarbon* 55(4):1889–1903.

Holliday, V. T. 1988 Genesis of a late Holocene soil chronosequence at the Lubbock Lake archaeological site, Texas. *Annals of the Association of American Geographers* 78:594–610.

Holliday, V. T. 2004 *Soils in Archaeological Research*. Oxford: Oxford University Press.

Horton, D. R. 1981 Water and woodland: The peopling of Australia. *Australian Institute of Aboriginal Studies Newsletter* 16:21–27.

Hughes, P. J. 1978 Weathering in sandstone shelters in the Sydney Basin and the survival of rock art. In C. Peasron (Ed.), *Conservation of Rock Art,* pp. 36–41. Sydney: Institute for the Conservation of Cultural Material.

Hughes, P. J. and R. J. Lampert 1977 Occupational disturbance and types of archaeological deposits. *Journal of Archaeological Science* 4:135–140.

Ingram, R. L. 1971 Sieve analysis. In R. E. Carver (Ed.), *Procedures in Sedimentary Petrology,* pp.49–69. New York: Wiley-Interscience.

Keys, B. O. 2009 *Engrained in the Past: Using Geoarchaeology to Understand Site Formation Processes at the Gledswood Shelter 1 Site, Northwest Queensland*. Unpublished BArch (Honours) thesis, Department of Archaeology, Flinders University, Adelaide.

Le Borgne, E. 1960 Influence de feu sur les proprietes magnetiques du sol et sur celles du schist et du grantie. *Annales de Geophysique* 16:159–195.

Lamb, L. 1996 Investigating changing stone technologies, site use and occupational intensities at Fern Cave, north Queesland. *Australian Archaeology* 42:1–7.

Lewis, S. C., M. K. Gagen, L. K. Ayliff, J. Zhao, W. S. Hantoro, P. C. Treble, J. C. Hellstrom, A. N. LeGrande, M. Kelley, G. A. Schmidt and B. W. Suwargadi 2011 High-resolution stalagmite reconstructions of Australian-Indonesian monsoon rainfall variablility during Heinrich stadial 3 and Greenland interstadial 4. *Earth and Planetary Science Letters* 303(1–2):133–142.

Linford, N., P. Linford and E. Platzman 2005 Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames Valley, UK. *Journal of Archaeological* Science 32(7):1037–1043.

Lowe, K. M., J. Shulmeister, J. M. Feinberg, T. Manne, L. A. Wallis and K. Welsh in review. Using soil magnetic properties to determine the level of onset of human settlement at Australian archaeological sites. *Geoarchaeology*.

Kershaw, A. P., P. T. Moss and S. van der Kaars 1997 Environmental change and the human occupation of Australia. *Anthropologie* 35:35–43.

Magee, J. W., J. M. Bowler, G. H. Miller and D. L. G. Williams 1995 Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 113:3–42.

Magee, J. W. and G. H. Miller 1998 Lake Eyre palaeohydrology from 60 ka to the present: Beach ridges and glacial maximum aridity. *Palaeogeography, Palaeoclimatology, Palaeoecology* 144:307–329.

Maher, B. A. and R. M. Taylor 1988 Formation of ultrafine-grained magnetite in soils. *Nature* 336:368–371.

Marmet, E., M. Bina, N. Fedoroff and A. Tabbagh 1999 Relationships between human activity and the magnetic properties of soils: A case study in the medieval site of Roissy-en-France. *Archaeological Prospection* 6:161–170.

Marwick, B. 2002 Milly’s Cave: Evidence for human occupation of the inland Pilbara during the Last Glacial Maximum. In S. C. Ulm, C. Westcott, J. Reid, A. Ross, I. Lilley, J. Prangnell and L. Kirckwood (eds), *Barries, Borders, Boudnaries: Procedings ofs the 2001 Australian Archaeological Association Annual Conference,* pp. 21–33. Tempus 7. St Lucia: Anthropology Musem, The Univeristy of Queensland.

Marwick, B. 2005 Element concentrations and magnetic susceptibility of anthrosols: Indicators of prehistoric human occupation in the inland Pilbara, Western Australia. *Journal of Archaeological Science* 32:1357–1368.

McGlone, M. S., A. P. Kershaw and V. Markgraf 1992 El Niño/Southern Oscillation climatic variability in Australasian and South American palaeoenvironmental records. In H. F. Diaz and V. Markgraf (eds), *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*, pp. 435–462. Cambridge: Cambridge University Press.

McManus, J. 1988 Grain size determination and interpretation. In M. E. Tucker (ed.), *Techniques in Sedimentology,* pp. 63–85. Oxford: Blackwell.

Mentzer, S. M. 2012 Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory*:1–53.

Meterology, Bureau of 2013 *Monthly mean maximum temperature: Richmond Post Office.* [Online]. Commonwealth of Australia, Melbourne. Available: http://www.bom.gov.au/climate/averages/tables/cw_030045.shtml [Accessed January 31 2013].

Miller, G. H., J. M. Magee and A. J. T. Jull 1997 Low latitude glacial cooling in the Southern Hemisphere from amino acids in emu eggshells. *Nature* 385:241–244.

Mohtadi, M., D. W. Oppo, S. Steinke, J.-B. W. Stuut, R. De Pol-Holz, D. Hebbeln and A. Lückge 2011 Glacial to Holocene swings of the Australian-Indonesian Monsoon. *Nature Geoscience* 4:540–544.

Mol, L. and H. A. Viles 2012 The role of rock surface hardness and internal moisture in tafoni development in sandstone. *Earth Surface Processes and Landforms* 37:301–314.

Nielsen, A. E. 1991 Trampling the archaeological record: An experimental study. *American Antiquity* 56:483–503.

Nott, J. F. and D. M. Price 1999 Waterfalls, floods and climate change: Evidence from tropical Australia. *Earth and Planetary Science Letters* 171:267–276.

O'Connell, J. F. and J. Allen 2004 Dating the colonization of Sahul (Pleistocene Australia–New Guinea): A review of recent research. *Journal of Archaeological Science* 31:835–853.

O'Connor, S., P. Veth and A. Barham 1999 Cultural versus natural explanations for lacunae in Aboriginal occupation deposits in northern Australia. *Quaternary International* 59:61–70.

O’Connor, S. and P. Veth 2006 Revisiting the past: Changing interpretations of Pleistocene settlemetn subsistence and demopgraphy in northern Australia. In I. Lilly (ed.) *Archaeology of Oceania: Australia and the Pacific Islands,* pp. 31–47. Blackwell Studies in Global Archeology. Oxford: Blackwell.

Petherick, L., H. A. McGowan and B. S. Kamber 2009 Reconstructing transport pathways for late Quaternary dust from eastern Australia using the composition of trace elements of long traveled dusts. *Geomorphology* 105:67–79.

Petherick, L. M., P. T. Moss and H. A. McGowan 2011 Climatic and environmental variability during the termination of the last glacial stage in coastal eastern Australia: A review. *Australian Journal of Earth Sciences* 58(6):563–577.

Prebble, M., R. Sim, J. Finn and D. Fink 2005 A Holocene pollen and diatom record from Vanderlin Island, Gulf of Carpentaria, lowland tropical Australia. *Quaternary Research* 64:357–371.

Rayment, G .E. and D. J. Lyons 2011 *Soil Chemical Methods – Australasia*. CSIRO Publishing, Collingwood.

Reeves, J. M., A. R. Chivas, A. García and P. De Deckker 2007 Palaeoenvironmental change in the Gulf of Carpentaria (Australia) since the last interglacial based on Ostracoda. *Palaeogeography, Palaeoclimatology, Palaeoecology 246*:163–187.

Reeves, J. M., A. R. Chivas, A. García, S. Holt, M. J. J. Couapel, B. G. Jones, D. I. Cendón and D. Fink 2008 The sedimentary record of palaeoenvironments and sea level change in the Gulf of Carpentaria, Australia, through the last glacial cycle. *Quaternary International* 183(1):3–22.

Reeves, J. M., H. C. Bostock, L. K. Ayliffe, T. T. Barrows, P. De Deckker, L. S. Devriendt, G. B. Dunbar, R. N. Drysdale, K. E. Fitzsimmons, M. K. Gagan, M. L. Griffiths, S. G. Haberle, J. D. Jansen, C. E. Krause, S. Lewis, H. V. McGregor, S. D. Mooney, P. Moss, G. Nanson, A. Purcell and S. van der Kaars 2013 Palaeoenvironmental change in tropical Australasia over the last 30 000 years a synthesis by the OZ-INTIMATE group. *Quaternary Science Reviews* 74:21–34.

Richardson, N. 1992 Conjoin sets and stratigraphic integrity in a sandstone rockshelter: Kenniff Cave (Queensland, Australia). *Antiquity* 66:408–418.

Richardson, N. 1996 Seeing is believing: a graphical illustration of the vertical and horizontal distribution of conjoined artefacts using DesignCAD 3D. In S. Ulm, S., I. Lilley and A Ross (eds), *AustralianArchaeology '95: Proceedings of the 1995 Australian Archaeological Association Annual Conference*, pp. 81–95. *Tempus* 6. St. Lucia: Anthropology Museum, Department of Anthropology and Sociology, University of Queensland.

Schiffer, M. B. 1987 *Formation Processes of the Archaeological Record*. Albuquerque: University of New Mexico Press.

Shiau, L.-J., M.-T. Chen, S. C. Clemens, C.-A. Huh, M. Yamamoto and Y. Yokoyama 2011 Warm pool hydrological and terrestrial variability near southern Papua New Guinea over the past 50k. *Geophysical Research Letters* 38:L00F01, doi:10.1029/21010GL045309.

Shulmeister, J. and B. G. Lees 1995 Pollen evidence from tropical Australia for the onset of an ENSO-dominated climate at c. 4000 BP. *The Holocene* 5:10–18.

Smart, J. 1973 *Gilberton, Queensland 1:250,000 Geological Series, Explanatory Notes, Sheet SE54-16,* Canberra: Australian Government Publishing Service.

Smith, M. A. 1989 The case for a resident human population in the Central Australian ranges during full glacial aridity. *Archaeology in Oceania* 24(3):93–105.

Smith, M. A. 1993 Biogeography, human ecology and prehistory in the sandridge deserts. *Australian Archaeology* (37):35–50.

Smith, M.A. 2009 Late Quaternary landscapes in Central Australia: Sedimentary history and palaeoecology of Puritjarra rock shelter. *Journal of Quaternary Science* 24(7):747–760.

Spooner, M. I., T. Barrows, P. De Deckker and M. Paterne 2005 Palaeoceanography of the Banda Sea, and late Pleistocene initiation of the Northwest Monsoon. *Global and Planetary Change* 49:28–46.

Sullivan, M. E. and P. J. Hughes 1983 The geoarchaeology of the Sydney Basin sandstones. In R. W. Young and G. C. Narson (eds), *Aspects of Australian Sanstone Landscape,* pp. 120–126.

Woolongong: Australian and New Zealand Geomorphology Group Special Publication, University of Woolongong.

Stein, J. K. and W. R. Farrand 2001 *Sediments in Archaeological Context*. Salt Lake City: University of Utah Press.

Stoops, G. 2003 *Guidelines for Analysis and Description of Soil and Regolith Thin-Sections*. Madison: Soil Science Society of America, Inc.

Straus, L. G. 1990 Underground archaeology: Perspectives on caves and rockshelters. *Archaeological Method and Theory* 2:255–304.

Thompson, R. and F. Oldfield 1986 *Environmental Magnetism*. London: Allen and Unwin.

Turkington, A. V. and T. R. Paradise 2005 Sandstone weathering: A century of research and innovation. *Geomorphology* 67:229–253.

Veth, P. 1989 Islands in the interior: A model for the colonization of Australia's arid zone. *Archaeology in Oceania,* 24:81–92.

Veth, P., M. Smith, J. Bowler, K. Fitzsimmons, A. Williams and P. Hiscock 2009 Excavations at Parnkupirti, Lake Gregory, Great Sandy Desert: OSL ages for occupation before the last glacial maximum. *Australian Archaeology* 69:1–10.

Wallis, L. A., K. Fitzsimmons, K. M. Lowe, B. Keys, I. Moffat, X. Carah, N. Wright and S. Mentzer Unpublished data. Site report on Gledswood Shelter 1. The University of Queensland, St. Lucia.

Wallis, L. A., B. Keys, I. Moffat and S. Fallon 2009 Gledswood Shelter 1: Initial radiocarbon dates from a Pleistocene aged rockshelter site in northwest Queensland. *Australian Archaeology* 69:71–74.

Wallis, L. A., H. Smith and D. Smith 2004 Investigations of Aboriginal hearth sites along the Flinders River, inland northwest Queensland. *The Artefact* 27:59–76.

Ward, I. A. K. and P. Larcombe 2003 A process-orientated approach to archaeological site formation: Application to semi-arid northern Australia. *Journal of Archaeological Science* 30:1223–1236.

Webster, P. J. and N. A. Streten 1978 Late Quaternary ice age climates of tropical Australasia: interpretations and reconstructions. *Quaternary Research* 10:279–309.

Williams, A., S. Ulm, A. Cook, M. Langley and M. Collard 2013 Human refugia during the last glacial maximum and terminal Pleistocene: A geospatial analysis of the 25–12 ka Australian archaeological record. *Journal of Archaeological Science* 40:4612–4625.

Williams, M., E. Cook, E., S. van der Kaars, T. Barrows, J. Shulmeister and P. Kershaw 2009 Glacial and deglacial climatic patterns in Australia and surrounding regions from 35 000 to 10 000 years ago reconstructed from terrestrial and near-shore proxy data. *Quaternary Science Reviews* 28(23–24):2398–2419.

Woodward, J. C. and P. Goldberg 2001 The sedimentary records in Mediterranean rockshelters and caves: Archives of environmental change. *Geoarchaeology* 16:327–354.

Wyrwoll, K.-H., J. M. Hopwood and G. Chen 2012 Orbital time-scale circulation controls of the Australian Summer monsoon: A possible role for mid-latitude Southern Hemisphere forcing? *Quaternary Science Reviews* 35:23–28.

CHAPTER 5

GROUND-PENETRATING RADAR AND BURIAL PRACTICES IN WESTERN ARNHEM LAND, AUSTRALIA

Chapter 5 is reproduced from the article submitted to *Archaeology in Oceania* and is part of the thesis question regarding burial practices. It has been reformatted for this thesis chapter.

Lowe, K. M., L. A. Wallis, C. Pardoe, B. Marwick, C. Clarkson, T. Manne, M. A. Smith and R. Fullagar 2014 Ground-penetrating radar and burial practices in Western Arnhem Land, Australia. Archaeology in Oceania 49:148–157.

5.1 Abstract

A GPR survey was carried out in advance of archaeological excavations at Madjedbebe (formerly known as Malakunanja II), a sandstone rockshelter in western Arnhem Land (Australia) containing numerous Aboriginal burials. GPR revealed subsurface patterning of rocks in the shelter deposits and archaeological excavation demonstrated that these were related to burials. Post-excavation, GIS and statistical analysis further elucidated the relationship between the rocks and human burials. This integration of detailed mapping, GPR and excavation afforded the opportunity to test a way to identify unmarked burials using GPR in sandstone rockshelters and to document a marker for burial identification in this region. Application of the methodology developed through this case study provides a useful management tool for Indigenous communities and other heritage practitioners.

5.2 Introduction

In Australia, where the density of burials tends to correlate strongly with population densities, and where burials may be found within residential spaces, developing methods for the detection of burials is an area of keen research and management interest. Geophysical techniques provide a non-invasive way to investigate subsurface features (Gaffney and Gater 2003; Johnson 2006; Witten

2006), and for these reasons these techniques, particularly GPR, have become very popular in projects where burials are anticipated.

GPR works by transmitting electromagnetic energy in the form of radar waves into the ground (Bevan 1998; Conyers 2012). When the wave encounters a contrasting material in the soil (such as air voids, stone or moisture content), a reflection occurs, sending part of the wave back to the surface, where it is received and recorded. The remainder of the wave continues downward until it too is reflected back to the surface by deeper objects, or dissipated through absorption by subsurface materials. The depth of radar wave penetration and velocity is highly dependent on soil type and moisture conditions, or the dielectric properties (the ability of a radar wave to hold and transmit an electric charge).

Conyers (2006:66) suggests that the physical features frequently associated with burials that can be identified by GPR include: 1) 'undisturbed' sediment below and surrounding the grave shaft; 2) a buried coffin or human body and associated artefacts; 3) 'disturbed' sediment used to fill the grave shaft; and 4) any surface sediments that have accumulated above the shaft and surroundings after internment (Conyers 2006:66). The identification of areas of soil compaction and void spaces are also of particular relevance, especially in Indigenous burials. As Lowe (2012) has discussed, it is for these reasons, coupled with the ease of access to GPR equipment, that this has become the most routinely used geophysical instrument for identifying burials in Australia (cf. Bladon et al. 2011; Brown et al. 2002; L’Oste-Brown et al. 1995; Moffat et al. 2010; Powell 2004, 2010; Randolph et al. 1994; von Strokirch 1999; Yelf and Burnett 1995).

Yet GPR does not offer fool-proof detection of all graves, sometimes producing false positives due to other sources of disturbance or, in cases where graves are indistinguishable from the surrounding strata, false negatives or no results (Bevan 1991; Dalan et al. 2010; Davenport 2001; Nobes 1999). Unmarked burials, which are common in Australian historic archaeology and almost exclusively the case in Australian Indigenous archaeology, present specific challenges. The particular form of these burials (e.g. bundle, cremation, limited grave goods, shallow depth, no coffin, etc; see Meehan 1971) and the nature of the geologically ancient sediments into which interment occurs, often impedes their identification with GPR. Further, in areas where the sedimentary matrix consists of gravelly, shelly or cobble rich sediments, there can be significant ‘distortions’ in the data for both the disturbed area of the grave shaft and undisturbed areas adjacent to the grave, adding to the complexity of interpretation (Conyers 2006). The limited case studies with which to compare and contrast results in Australia also means interpretation is often speculative, with excavation rarely carried out to confirm the specific nature of GPR-identified anomalies.

In this paper we detail how GPR was combined with archaeological excavation data using a GIS approach to test and identify numerous unmarked burials in a rockshelter context. The results were also tested with statistical analysis to confirm that the documented association was deliberate rather than random. Burial methods across Arnhem Land are known ethnographically to include secondary rockshelter burials, excarnation, tree burial and hollow log coffins (Meehan 1971), though there is little evidence of why certain individuals might receive particular treatment, or whether this changed through time. While several accounts have been documented in our study region, none have been reported for our study site.

In addition, changing legal codes over the past 30 years defining Indigenous peoples as the primary holder of rights regarding decision-making in respect to their heritage has done much to improve the relationship between archaeologists and Traditional Owners, though it has also resulted in fewer burial site investigations being carried out in Australia. When our research partners, the Gundjeihmi Aboriginal Corporation (GAC) representing the Traditional Owners of the study area, the Mirarr, granted permission to study the Madjedbebe rockshelter in northern Australia as part of broader heritage initiatives, it afforded a rare opportunity to perform a detailed geophysical survey prior to archaeological ground disturbance.

5.3 The Madjedbebe Site

Madjedbebe (formerly known as Malakunanja II) is a Pleistocene-aged rockshelter located in Arnhem Land, Australia (Figure 5.1). The shelter is a narrow, northwest-facing sandstone overhang at the base of the Arnhem Land Plateau escarpment located approximately 9 km west of the East Alligator River. The shelter wall contains a gallery of pigment art, and the shelter floor is generally flat, sandy and mostly vegetation free. The archaeological deposits at Madjedbebe comprise a ~70 cm thick Holocene-aged shell midden unit, underlain by a further ~3 m of late Pleistocene-aged cultural deposits (Kamminga and Allen 1973). This subsoil parent material is a mix of sand and silt weathered from the adjoining quartzose sandstone escarpment of the Middle Proterozoic Kombolgie Formation (East 1996: 40). For this study, it is only the shell midden unit with which we are concerned.

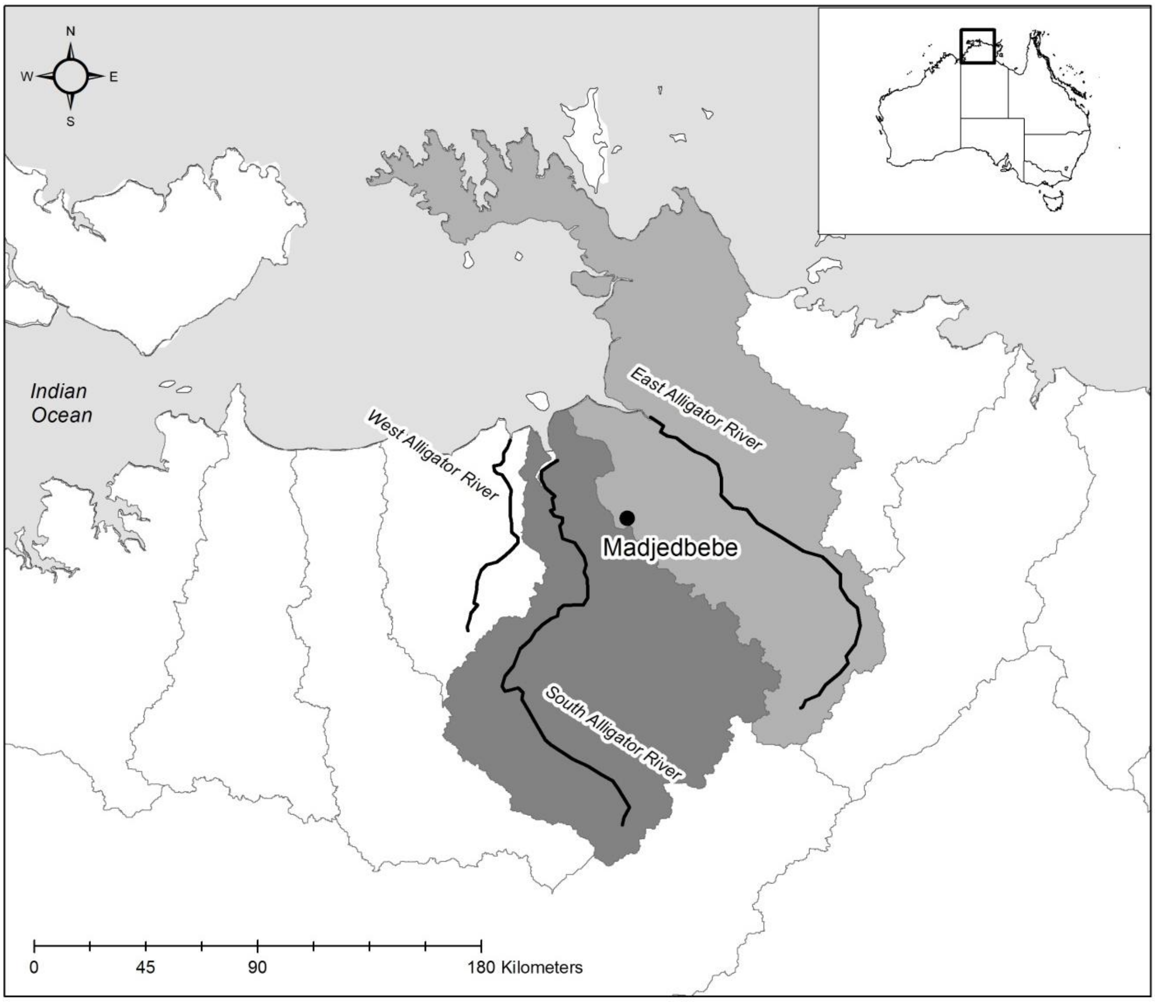

Figure 5.1 **Study area location in western Arnhem Land. Areas in shaded grey indicate the East and South Alligator River catchments.**

Madjedbebe has been the focus of several archaeological investigations, being first excavated in 1972 (Kamminga and Allen 1973) and again in 1989 (Roberts et al. 1990); the latter investigation yielded luminescence dates of 50,000–60,000 years BP. While these investigations involved only small test-pits they did reveal that burials were present within the midden unit, though they were assumed to be few in number and primarily secondary bundle burials (Smith 1989). This prior identification of burials caused concern when the site was to be reinvestigated and thus a geophysical survey was conducted prior to re-excavation to allow researchers to be better informed about what they might encounter.

5.4 Methods

In late 2011, a geophysical survey grid measuring 8 x 18 m was established adjacent to the Madjedbebe shelter wall (Figure 5.2). This grid was used to conduct two surveys: one with transects spaced 0.25 m, running parallel to the shelter wall and the other with transects spaced 0.50 m, running perpendicular to the shelter wall. This methodology provided the necessary high spatial resolution for discerning small, discrete features. GPR data were collected with a Geophysical Survey Systems, Inc. (GSSI) SIR-3000, 400 MHz antenna and a model 620 survey wheel. Sixteen-bit data were collected with an 80 nS time window, 512 samples/scan and with 25 scans/meter. Data were processed and converted into slice maps using GPR-SLICE v7.0. Time slices were made using the hyperbola fitting function to estimate the relative dielectric permittivity, which is calculated from the two-way travel time to depth (Goodman and Piro 2013). These depth estimates generated in the software were then verified in the excavations.

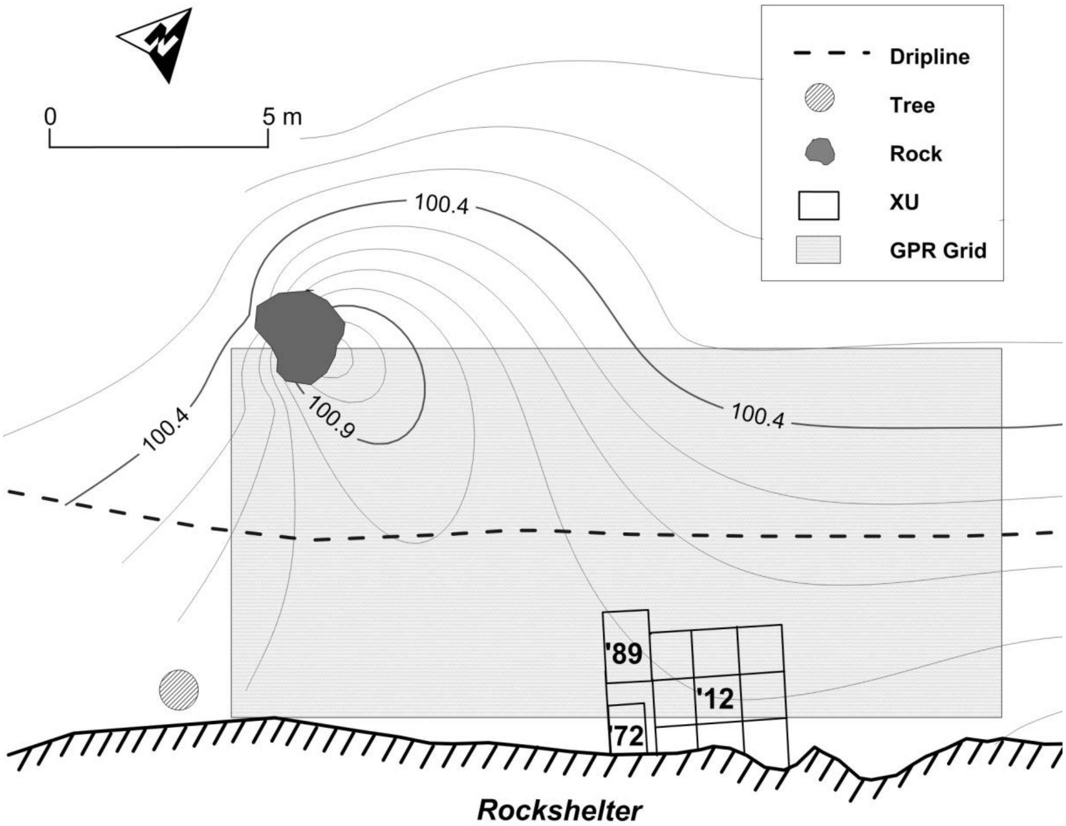

Figure 5.2 **Topographic map showing the location of the 1972, 1989 and 2012 excavation units (XU) and that of the 2011 GPR survey at Madjedbebe.**

All excavated material, with the exception of the human remains, was dry-sieved through 3 and 7 mm sieves and sorted in the field. A complete 1 x 1 m bulk sample for flotation analysis was retained from every spit of C2, as well as from all hearth features. Analysis of collected material from the investigations, including radiocarbon and optically stimulated luminescence dating, are on-going and therefore, are not included as part of this study.

A comprehensive mapping regime was designed and implemented to allow the creation of a high precision map of the site as a means by which to digitally archive the spatial excavation data. This form of total station archaeology is highly effective at enabling rapid data integration and for understanding site formation processes (cf. Marean et al. 2007; McPherron 2005), as well as for managing and analysing field data (McCoy and Ladefoged 2009; Tripcevich and Wernke 2010). A dictionary of all collected data was established and used to build a database/attribute file and vector data for analysis in ESRI ArcGIS 10.2. These data were used to examine the spatial relationships between rock deposits and human burials within the sedimentary sequence.

The output of the collected GIS data was also used to look at the statistical relationships between particular archaeological features. While one could visually observe and develop a ‘sense of’ some of these patterns during excavation, they were rigorously verified post-excavation statistically. In this case, resampling methods and geometric morphometry was used to investigate the relationship between human burials and rocks by determining if the rocks were randomly or deliberately (anthropogenic) positioned as part of the burial practice. Statistical measurements were computed in R3.0.1 and RStudio 0.97.336 using the GIS vector data of both rock and burial features.

5.5 Results

The GPR data revealed the complex nature of the shelter deposits. The local sandstone geology was a critical factor, with large rocks in the deposit causing very strong reflections and slight contrasts in the data (Figure 5.3a). These were interpreted as dense roof fall since the reflections occurred directly below and beyond the shelter’s drip-line. A sub-set of the GPR data/dataset adjacent to the shelter wall and within the drip-line was selected for additional post-processing to investigate the area within the drip-line that appeared to have no roof fall and where human activity would likely have been more regular.

Original GPR reflections became much clearer after the selected sub-set of the original data set was processed. The sub-set revealed a number of strong reflections within the drip-line and adjacent to the shelter wall (Figure 5.3b). These were apparent in both the amplitude slices and reflection profiles, and defined easily even amongst the shell midden (Figure 5.4). Excavation revealed that these reflections were from medium (15–50 cm diameter) sized rocks. While other hyperbolic reflections were apparent in the reflection profiles resembling those defined as rocks (see Figure 5.4), these were not excavated and therefore their cause is unknown.

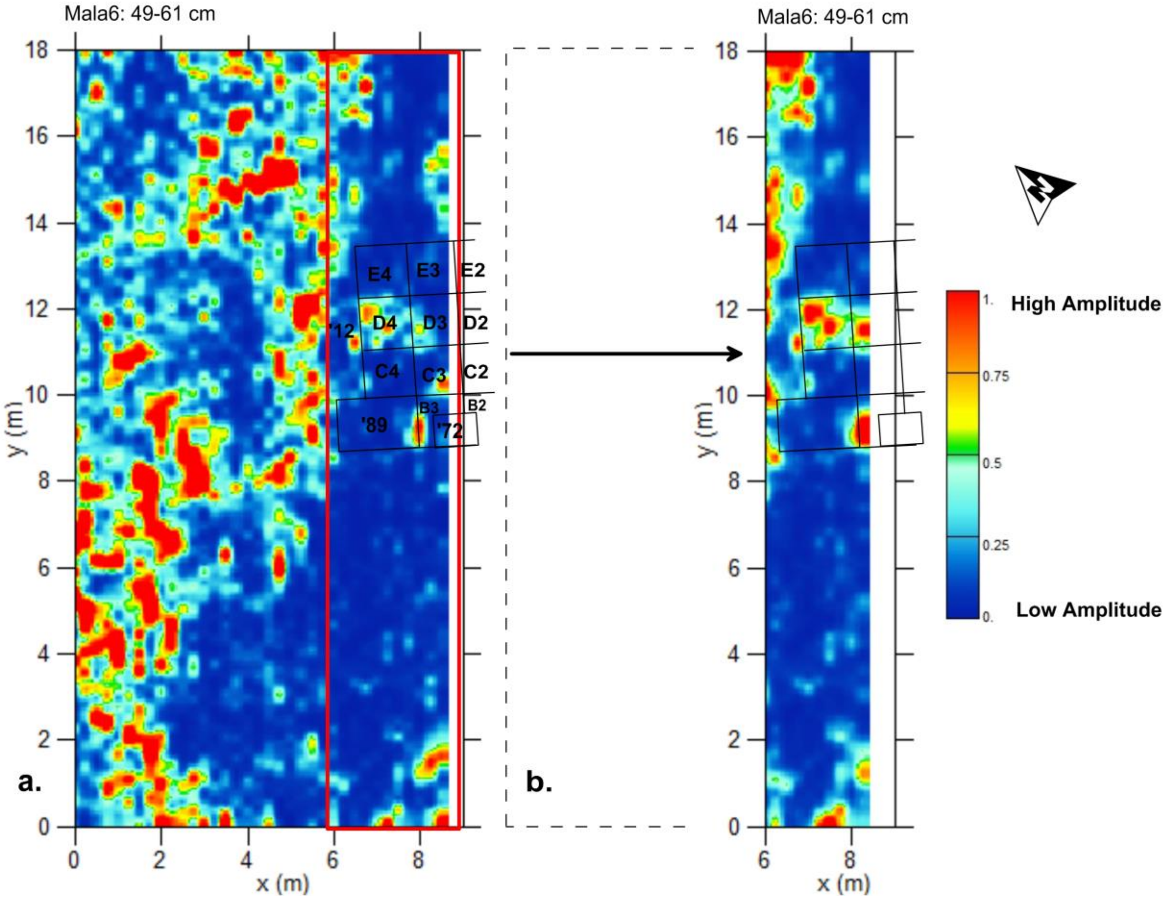

Figure 5.3 a. Amplitude slice-maps of Madjedbebe (49–61 cm). Areas with higher reflections denoted by yellow and red. b. Re-sampled amplitude sub-set. Squares E2, D2, C2 and B2 were located under the shelter wall and were not surveyed.

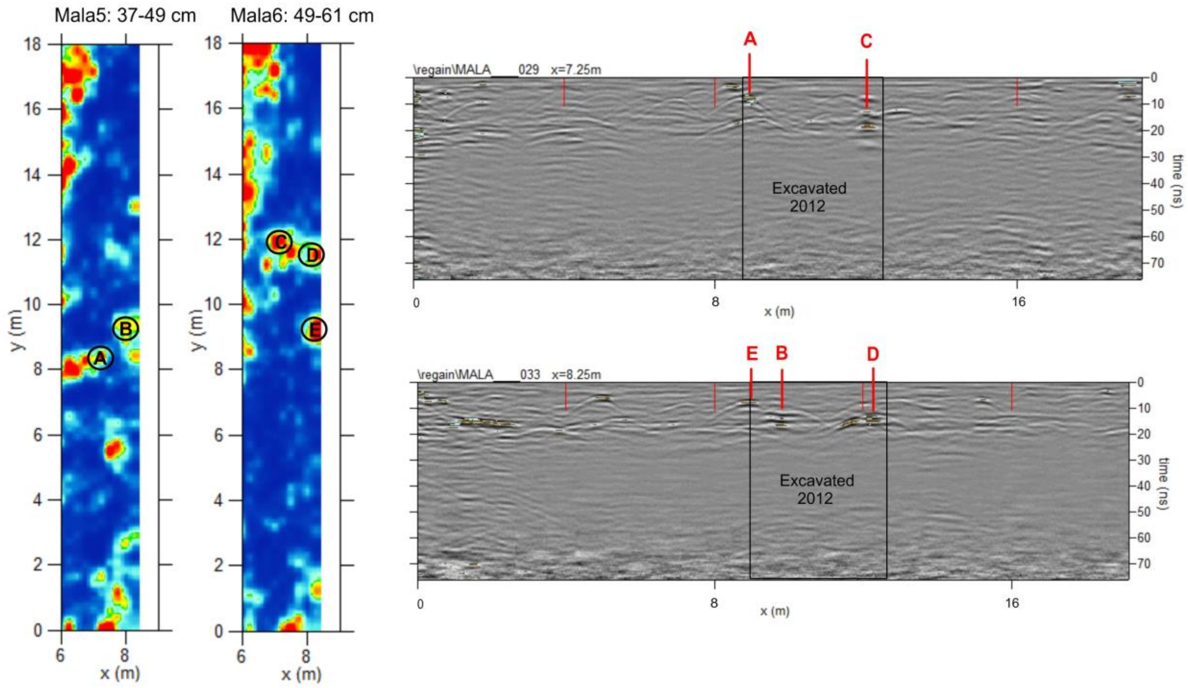

Figure 5.4 Re-sampled selected amplitude slice-map of sub-sets (left) showing selected (A-E) high amplitude features/concentrations in two selected reflection profiles (right). Areas outside black rectangle are unexcavated.

The 2012 Madjedbebe excavations unearthed 17 individuals (coded as skeletal remains, hereafter SR) in various states of completeness (Figure 5.5). These comprised predominantly primary interments (n=13) dug into, or just through, the shell midden unit into the uppermost level of the underlying sand unit. All of the burials contained minimal amounts of grave goods and occurred in both flexed and extended positions.

Although narrow GPR survey transects (i.e. 0.25 m) were used at Madjedbebe, the identification of human bones, burial shafts or void spaces within the shell midden unit in the collected GPR data was not possible. However, at least nine of the burials were associated with rocks, a tradition similar to that documented by Schrire (1982) at the nearby site of Nawamoyn. At Madjedbebe, most rocks were placed on the individual’s head and, in two instances, rocks were placed on both the head and feet (SR1 and SR5), while one burial had a rock placed only on the feet (SR4). With the exception of two burials in a single grave (SR3 and SR14), the rocks associated with each burial were similar in size, averaging 20 cm in diameter—a size small enough to be moved by an individual, but unlikely to be displaced by animal activity or bioturbation as indicated by the relatively intact and articulated nature of the burials. Plotting of the rocks during excavation revealed that they coincided with the burials (Figure 5.6) and when compared with the GPR data, it became clear that the high amplitude reflections in the GPR data corresponded with these rocks and, in turn, with the primary interments (Figure 5.7).

Considering that naturally deposited sandstone rocks were also present on the surface and in the deposits at the site, statistical analysis was used to determine if the association of the rocks with the burials was random or deliberate (anthropogenic). To test this, the GIS data of all skeletal remains and rocks in the excavated deposits were used to compute the probability that the observed amount of overlap was due to random processes. One thousand random arrangements of the rock polygons were simulated in the excavation area and the area of overlap with the skeleton polygons (whose locations were kept constant) was computed for each random arrangement. The mean area of overlap in the random permutations was 0.34±0.09 m^2, compared to the observed area of overlap of 0.53 m^2. Only 2.5% of the random permutations have an overlap area equal to or greater than the observed area, indicating that the observed area of overlap of rocks and skeletons is significantly non random (Figure 5.8) (see http://dx.doi.org/10.5281/zenodo.10616 for supplementary information).

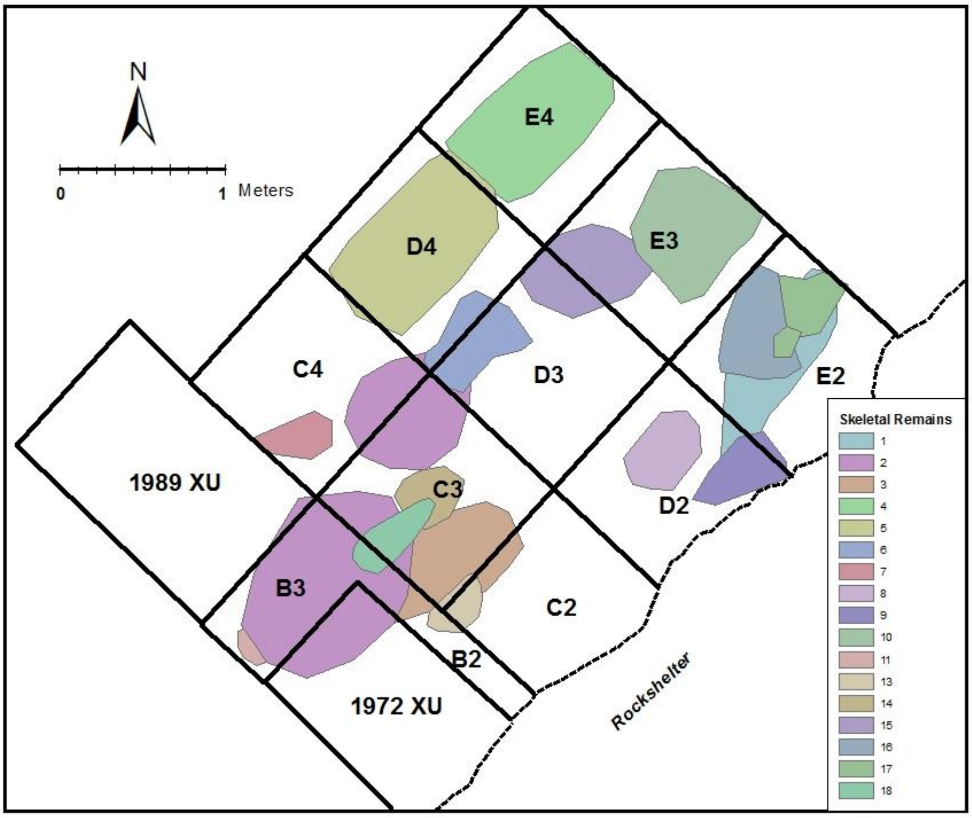

Figure 5.5 Location of burials identified in the nine 1 x 1 m test-pits (Squares C2, C3, C4, D2, D3, D4, E2, E3 and E4) and two smaller test-pits (B2 and B3).

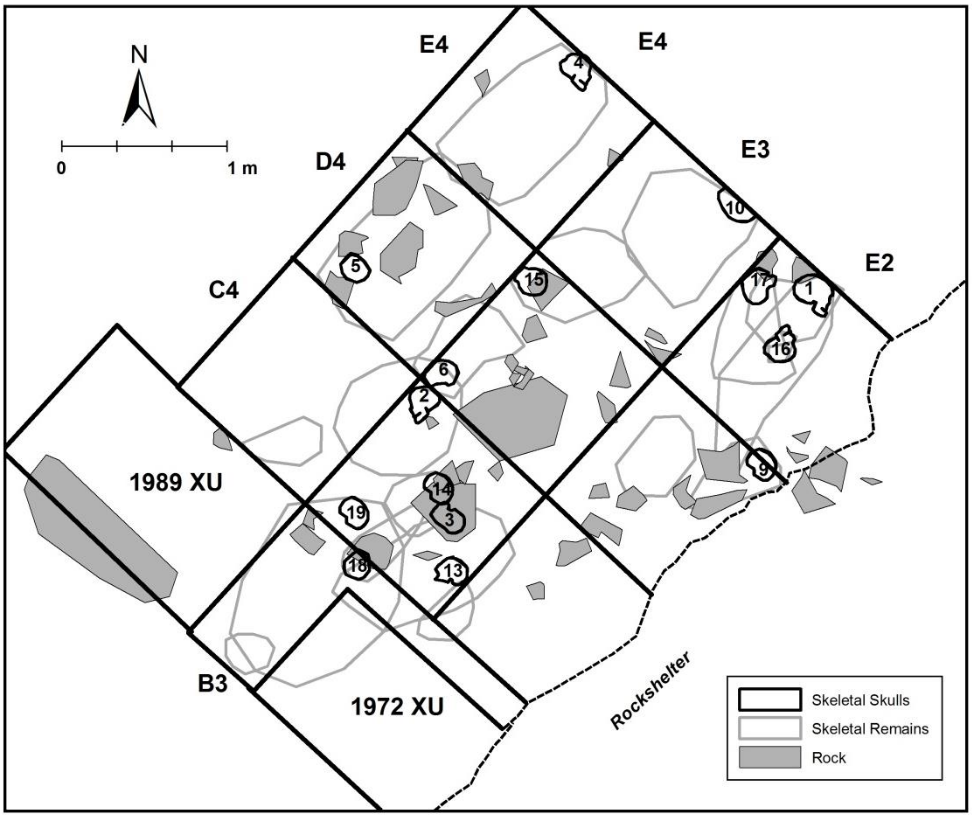

Figure 5.6 Plan view map showing the location of rocks on the skeletal remains.

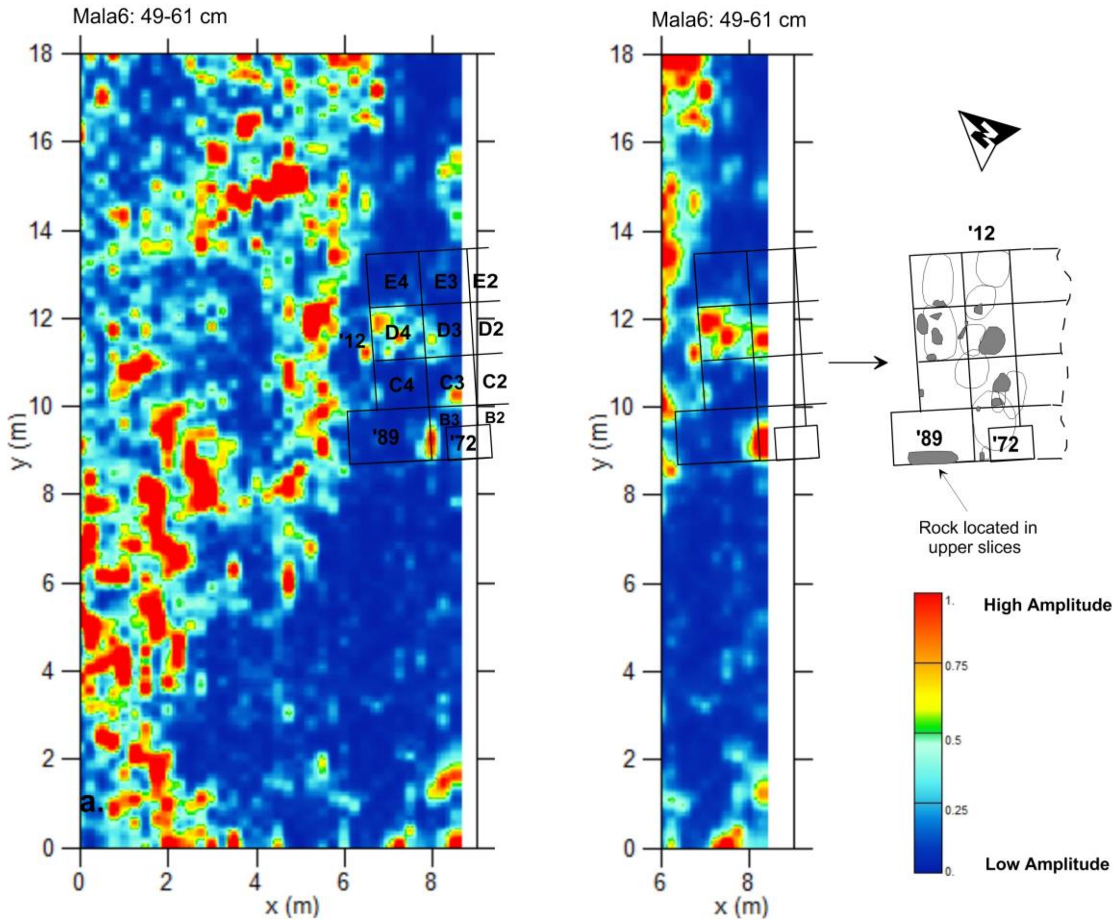

Figure 5.7 Both amplitude slice-map and sub-set showing the cause of the high reflections; cluster of rocks identified in the 2012 excavation (grey circles). Burials are noted as circles.

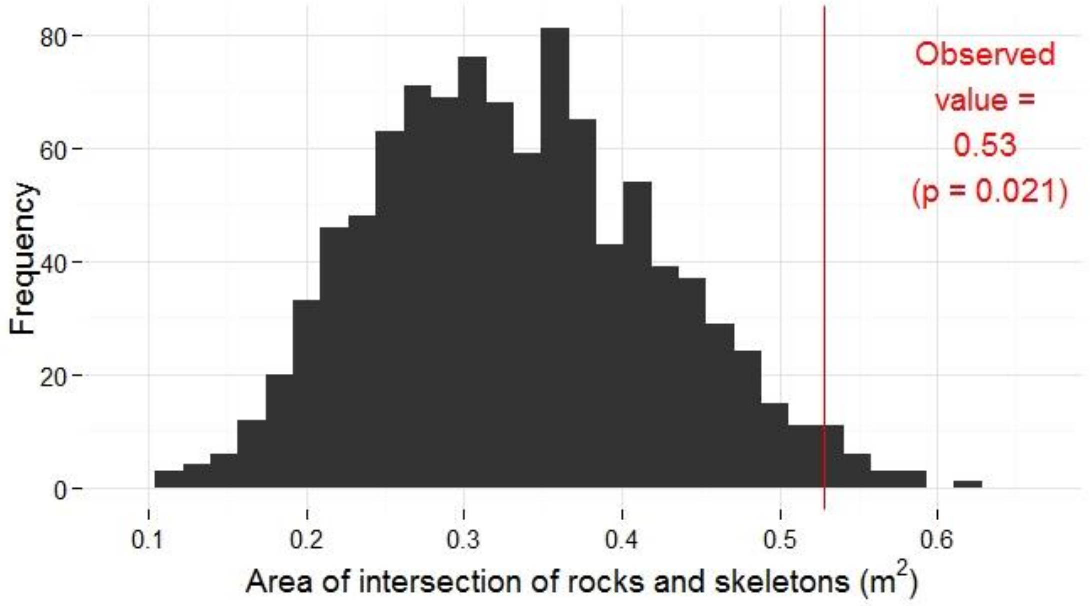

Figure 5.8 Distribution of areas of overlap of rocks on burials resulting from 1000 random permutations of rock locations.

5.6 Discussion

It was expected that burials would be present at Madjedbebe, which were thought to have caused alterations in the subsurface material. However, as the burials were initially anticipated to be small secondary bundle burials, the initial geophysical survey was designed with the primary goal of mapping more distinctive and larger features such as bedrock and roof fall. Even when a sub-set of the GPR data was selected for detailed post-data processing, Conyers' (2006: 66) list of four physical features used for geophysical burial identification was largely inapplicable since no changes in natural soil or surrounding material were apparent, coffins were not used, and vertical shafts were impossible to distinguish in the shell-rich deposits. The GPR survey thus did not identify grave cuts or fill; it was the combination of ethnographic and archaeological evidence with detailed GIS plots that demonstrated the mortuary practice involving placement of rocks over the burials.

Much research in Australian archaeology has explored regional variations in material culture (e.g. tula adzes, cylcons), burials, rock art and biology, and attempts have been made to utilise the results to extrapolate past territorial organisation (e.g. David 1991; David and Chant 1995; David and Cole 1990; Franklin 2004; McDonald 2008; Pardoe 1988, 1994, 1995; Wade et al. 2011). With respect to mortuary practices, any regional patterning present may be strongly dependent on external—rather than cultural—factors such as the presence of trees suitable for burial or excarnation (flesh removal), a soft substrate into which to dig a grave, or rockshelters for placement of bundles.

The ethnographic and archaeological documentation of burial practices amongst groups in the Arnhem Land region has demonstrated that variations exist. The Gagadju (Kakadu) were reported to have taken the body into the bush, cover it with grass and leaves, then earth and finally stones to discourage dogs from digging the bodies up (Berndt and Berndt 1992:463; Spencer 1914:240-9). At the Nawamoyn rockshelter site, not far from Madjedbebe, archaeological evidence for both an intact flexed and an extended burial has been observed (Schrire 1982). It was noted that the body was placed on the surface of the midden and large rocks put on top, one of 36 kg on the ribs and two, of 23 kg and 12 kg, on the pelvis. Smaller rocks were placed on the legs just above the knees, potentially to protect the body from predators or as markers of its position (Schrire 1982:126). Among the Murngin of northeast Arnhem Land, a similar style of burial was practiced, but with the body placed face downward and not flexed (Warner 1969 [1937]:422).

Secondary burial is also common in Arnhem Land, with the body first being either excarnated in a platform built in a tree, or buried for a season, before disinterring and wrapping in paperbark to be placed elsewhere, perhaps on a rock ledge and into rockshelters (White 1967:431). At the rockshelter sites of Paribari and Malangangerr, also close to Madjedbebe, Schrire (1982:56) found abundant evidence of secondary burials in the form of bones that had been ‘burnt, broken and stuffed into the [rockshelter] niche packed around with grass, bark and other debris’. While this anthropogenic process does not require subsurface burial, when placed into rockshelters the remains can become buried by the natural accumulation of sediment through time; prior to the 2012 excavations it was thought that these would be the primary form of burial at Madjedbebe.

Our engagement with the Mirarr custodians who were involved in overseeing the excavations also provided insight into local burial practices. Although it was unknown explicitly why rocks were used as part of their mortuary practice, one possible reason may have been to protect the remains of the deceased from disturbance by scavenging animals such as dingoes (or Tasmanian tigers) as noted by Baldwin Spencer during his 1912 visit to this region (Batty et al. 2005:161). However, protecting the living from the spirits of the deceased may also have been another consideration (Mark Djandjomerr, pers. comm., July 2012).

Graves were dug into the shell midden deposit and rocks were placed on the individuals before being covered. These rocks were the source of the strong reflections in the GPR data, and detailed archaeological mapping and excavation verified their location. Statistical analysis of the rock subsurface distributions using resampling and geometric morphometry over the burials confirmed that the rock placement was unlikely to have resulted from random processes, and indicates deliberate placement of rocks and not natural roof fall deposition. While these are not considered as grave goods in the usual sense, the inclusion of the rocks placed on an individual’s head and/or feet was a cultural aspect of the burials, and introduced a substantially different physical element to the subsurface deposit that was detectable using geophysical techniques.

By integrating GPR with archaeological excavations, GIS and statistics we have provided a powerful way to identify human burials in this part of Arnhem Land. Despite rockshelters being common, and one of the most regularly excavated site types in Australia, there has been minimal work on geophysical investigations of Australian rockshelters (Conyers 2012), though internationally this is not the case (Conyers 2011:19; Horle et al. 2007; Porsani et al. 2010). In combination with GIS mapping and archaeological excavation, we have demonstrated the successful application of GPR in an Australian sandstone rockshelter environment. The GPR results provided information on subsurface material associated with geological features such as bedrock and roof fall and, secondly, cultural material, in the form of deliberately positioned rocks associated with human burials.

The success of this study has important implications for future investigations and/or management of other sites in Mirarr country and elsewhere. While in this instance the presence of a thick shell midden unit in the Madjedbebe site provided conditions conducive to bone preservation, sandstone environments are typically acidic and rarely preserve bone. In addition, water table fluctuation, soil fauna (e.g. ants, termites), soil acidity and mineralogy are also all known to strongly influence bone preservation. For deposits lacking suitable conditions for bone preservation, such as the Pleistocene levels of the Madjedbebe site, GPR identification of subsurface rocks could provide a tentative indication of burials, which might be further supported by subsequent excavations, GIS and statistical study. GPR identification of rock patterns in midden deposits at other sites in Arnhem Land might also alert researchers and managers to the possibility of burials being present, thereby allowing communities to be more informed prior to considering permission to excavate or in other cases, choose avoidance. Further, GPR can be used to investigate the spatial layout of these rockshelter sites, by defining subsurface geological features such as buried bedrock or areas affected by natural processes like roof fall concentrations.

5.7 Concluding Remarks

This research has highlighted the importance of detailed data recording and integration when attempting to investigate and map complex archaeological sites. Although GPR surveys are extremely rare in Australian rockshelter studies, the study described herein demonstrates their potential value. The integration of GPR and excavation results through GIS proved to be very beneficial in understanding burial practices at Madjedbebe because of the specific way individuals were interred at this particular site. The initial GPR study identified the presence of numerous subsurface rocks of unknown origin; subsequent excavation identified they were associated with 17 burials, and statistical analysis indicated the association was deliberate, rather than random. Studies such as this indicate the potential of GPR to shed light on intra- (individual burial and cemetery practices) and inter-site (regional variation and territorial organisation) variability, particularly where information about cultural history is lacking.

The partnership with the Mirarr community and the formal approval process adopted to facilitate its development and continuance were critical aspects of this project. While research at Madjedbebe is ongoing, this partnership could potentially lead to future research collaborations, offering additional opportunities to explore further applications of archaeological geophysics in Mirarr Country.

Acknowledgements

The authors are grateful to the custodians of Madjedbebe, the Mirarr Senior Traditional Owners, Yvonne Margarula and May Nango, and to our research partners, the Gundjeihmi Aboriginal Corporation, for granting permission to carry out this research and publish this paper—thank you for trusting us with your Old People. To David Vadiveloo and Justin O'Brien, your support, advice and guidance, especially during the field season, is graciously acknowledged. We also acknowledge the work of Jo Kamminga, Bert Roberts and the late Rhys Jones during earlier excavations at Madjedbebe. To the other members of the field crew and research team, thank you for all your efforts during the long field season, especially Billy Griffith for all the fabulous meals you prepared that kept us on our feet, and to Jessica Thompson for providing the information and protocols for the GIS mapping. This research was carried out as part of ARC Discovery Project DP110102864.

References

Batty, P., L. Allen and J. Morton 2005 *The Photographs of Baldwin Spencer*. Melbourne: Miegunyah Press.

Berndt, R. M. and C. H. Berndt 1992 *The World of the First Australians. Aboriginal Traditional Life: Past and Present*. Canberra: Aboriginal Studies Press.

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

Bevan, B. W. 1998 Geophysical Exploration for Archaeology: An Introduction to Geophysical Exploration. Midwest Archaeological Centre Special Report No. 1. Lincoln: National Park Service, Midwest Archaeological Centre.

Brown, S., S. Avery and M. Goulding 2002 Recent investigations at the Ebenezer Mission cemetery. In R. Harrison and C. Williamson (eds), *After Captain Cook: The Archaeology of the Recent Indigenous Past in Australia*, pp. 147–170. Lanham: Altamira.

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(4):249–257.

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

Conyers, L. B. 2011 Discovery, mapping and interpretation of buried cultural resources non-invasively with ground-penetrating radar. *Journal of Geophysics and Engineering* 8, S13–S22.

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

Dalan, R. A., B. W. Bevan, D. Goodman, D. Lynch, S. L. DeVore, S. Adamek, T. Martin, G. Holley and M. Michlovic 2011 The measurement and analysis of depth in archaeological geophysics: Tests at the Biesterfeldt Site, USA. *Archaeological Prospection* 18:245–265.

Dalan, R. A., S. L. DeVore and R. B. Clay 2010 Geophysical identification of unmarked historic graves. *Geoarchaeology* 25: 572–601.

Davenport, G. C. 2001 Remote sensing applications in forensic investigations. *Historical Archaeology* 35:87–100.

David, B. 1991 Fern Cave, rock art and social formations: rock art regionalisation and demographic models in southeastern Cape York Peninsula. *Archaeology in Oceania* 26:41–57.

David, B. and D. Chant 1995 *Rock Art and Regionalisation in North Queensland Prehistory*. Brisbane: Queensland Museum.

David, B. and N. Cole 1990 Rock art and regionalisation in north Queensland prehistory. *Antiquity* 64:788–806.

East, T. J. 1996 Landform evolution. In C. M. Finlayson and I. Von Oertzen (eds), *Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia*, pp. 37–55. London: Kluwer Academic Publishers.

Franklin, N. R. 2004 *Explorations of Variability in Australian Prehistoric Rock Engravings*. Oxford: British Archaeological Report International Series 1318.

Gaffney, C. and J. Gater 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing Ltd.

Goodman, D. and S. Piro 2013 *GPR Remote Sensing in Archaeology*. New York: Springer.

Horle, S., F. Huneau, A. Salomon and A. Denis 2007 Using the ground-penetrating radar to assess the conservation condition of rock-art sites. *Comptes Rendus Geosciences* 339:536–544.

Johnson, J. K. (ed.) 2006 *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Tuscaloosa: University of Alabama.

Kamminga, J. and H. Allen 1973 *Report of the Archaeological Survey: Alligator Rivers Environmental Fact-Finding Study*. Darwin: Government Printer.

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84.

Oste-Brown, S. L., L. Godwin, G. Henry, T. Mitchell and V. Tyson 1995 *Living Under the Act': Taroom Aboriginal Reserve 1911-1927. Cultural Heritage Monograph Series, Vol. 1.* Brisbane: Queensland Department of Environment and Heritage.

Marean, C. W., M. Bar-Matthews, J. Bernatchez, E. Fisher, P. Goldberg, A. I. R. Herries, Z. Jacobs, A. Jerardino, P. Karkanas, T. Minichillo, P. J. Nilssen, E. Thompson, I. Watts and H. M. Williams 2007 Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature* 449:905–908.

McCoy, M. D. and T. N. Ladefoged 2009 New developments in the use of spatial technology in archaeology. *Journal of Archaeological Research* 17:263-295.

McDonald, J. J. 2008 *Dreamtime Superhighway: An Analysis of Sydney Basin Rock Art and Prehistoric Information Exchange*. Terra Australis 27. Canberra: Australian National University E-Press.

McPherron, S. J. P. 2005 Artifact orientations and site formation processes from total station proveniences. *Journal of Archaeological Science* 32:1003–1014.

Meehan, B. 1971 *The Form, Distribution and Antiquity of Australian Aboriginal Mortuary Practices.* Unpublished MA thesis, University of Sydney, Sydney.

Moffat, I., L. A. Wallis, M. W. Hounslow, K. Niland, K. Domett and G. Trevorrow 2010 Geophysical prospection for late Holocene burials in coastal environments: Possibilities and problems from a pilot study in South Australia. *Geoarchaeology* 25:645–665.

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

Pardoe, C. 1988 The cemetery as symbol: The distribution of prehistoric Aboriginal burial grounds in southeast Australia. *Archaeology in Oceania* 23:1–16.

Pardoe, C. 1994 Bioscapes: The evolutionary landscape of Australia. *Archaeology in Oceania* 29:182–190.

Pardoe, C. 1995 Riverine, biological and cultural evolution in southeastern Australia. *Antiquity* 69:696–713.

Porsani, J. L., G. de Matos Jangelme and R. Kipnis 2010 GPR survey at Lapa do Santo archaeological site, Lagoa Santa karstic region, Minas Gerais state, Brazil. *Journal of Archaeological Science* 37:1141–1148.

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

Powell, K. 2010 *Grave Concerns: Locating and Unearthing Human Bodies*. Bowen Hills: Australian Academic Press.

Randolph, P., V. Wilson, C. Frampton and G. Merritt 1994 Rottnest Island Aboriginal Prisoners Cemetery: Delineation of extent using ground-penetrating radar. In M. Sullivan, S. Brockwell and A. Webb (eds), *Archaeology in the North: Proceedings of the 1993 Australian Archaeological Association Conference*, pp. 394–415. Darwin: North Australia Research Unit, Australian National University.

Roberts, R. G., R. Jones and M. A. Smith 1990 Thermoluminescence dating of a 50,000-year old human occupation site in northern Australia. *Nature* 345:153–56.

Schrire, C. 1982 *The Alligator Rivers: Prehistory and Ecology in Western Arnhem Land.* Terra Australis 7. Canberra Department of Prehistory: Research School of Pacific Studies, Australian National University.

Smith, M. A. 1989 Field notes. Archaeological excavations at Malakunanja II, July-August 1989. Unpublished field notes on file AIATSIS, Canberra.

Spencer, B. 1914 *Native Tribes of the Northern Territory of Australia.* London: Macmillan.

Tripcevich, N. and S. A. Wernke 2010 On-site recording of excavation data using mobile GIS. *Journal of Field Archaeology* 35(4):380–397.

von Strokirch, T. 1999 A report on a ground magnetic Survey over the Ebenezer Mission cemetery and Surrounds. Unpublished report to Aboriginal Affairs Victoria, Melbourne.

Wade, V., L. A. Wallis and Woolgar Valley Aboriginal Corporation 2011 Style, space and social interaction: An archaeological investigation of rock art in inland north Queensland, Australia. *Australian Archaeology* 72:23–34.

Warner, W. L. 1969 [1937] A Black Civilization: A Social Study of an Australian Tribe. Massachusetts: P. Smith, Gloucester.

White, C. 1967 The prehistory of the Kakadu people. *Mankind* 6:426–431.

Witten, A. J. 2006 *Handbook of Geophyics and Archaeology*. London: Equinox Publishing.

Yelf, R. and A. Burnett 1995 Ground-Penetrating Radar Survey of Unmarked Cemeteries at Taroom Aboriginal Reserve, Bundulla, Queensland. Unpublished report to the Department of Environment and Heritage, Rockhampton.

CHAPTER 6

INTEGRATING GEOARCHAEOLOGY AND MAGNETIC SUSCEPTIBILITY AT THREE SHELL MOUNDS: A PILOT STUDY FROM THE GULF OF CARPENTARIA, AUSTRALIA

Chapter 6 is reproduced from the article in *Journal of Archaeological Science* and is part of the thesis question regarding reoccupation at open sites. It has been reformatted for this thesis chapter.

Rosendahl, D., K. M. Lowe, L. A. Wallis and S. Ulm 2014 Integrating geoarchaeology and magnetic susceptibility at three shell mounds: A pilot study from the Gulf of Carpentaria, Australia. Journal of Archaeological Science 49:21–32.

6.1 Abstract

In coastal areas of the globe, open shell matrix sites are commonly used to establish regional chronologies of human occupation and identify patterns of cultural change, particularly for the Holocene, post-sea level stabilisation period. Despite this, many basic sedimentary analyses that are routinely applied to rockshelter deposits (e.g. geophysical characterisation, particle size etc) are rarely applied to these sites. Magnetic susceptibility, occasionally used in rockshelters, has never been used to investigate shell matrix sites in Australia, despite several international studies identifying its efficacy for other types of open sites. This paper reports a pilot project applying a range of conventional sedimentary and archaeological analyses, as well as magnetic susceptibility at three anthropogenic shell mounds on Mornington Island, Gulf of Carpentaria, Australia. Results are compared to, firstly, assess site integrity and, secondly, to ascertain whether magnetic signatures are related to cultural or natural site formation processes. The results establish that the mounds were repeatedly visited, despite the archaeological evidence, including radiocarbon ages, suggesting effectively 'instantaneous' deposition. This has important implications for studies of other shell mounds where the limitations of radiocarbon dating precision may also mask multiple deposition events.

6.2 Introduction

In Australia, shell matrix deposits dominate the Holocene archaeological record in coastal areas. Understanding the formation history of some of these sites—for example, the large shell mounds of Cape York Peninsula—is relatively clear-cut, as clearly alternating layers of shell-rich and shell-poor layers make it clear that there have been different periods of accumulation (Morrison 2010, 2013). In contrast, many smaller mound sites have no such evidence for stratigraphic layering, instead appearing as a single homogenous deposit dominated by shell, characteristically with a thin sediment-rich uppermost unit, with nuanced, if any, shifts in dominant faunal composition (Faulkner 2013; Morrison 2013; Rosendahl 2012; Shiner et al. 2013). From such deposits researchers typically obtain, at best, two radiocarbon determinations (one for the surface and one for the base), which often produce ages that are statistically the same with large error margins, and an absence of local marine reservoir calibration values applied (cf. Ulm and Reid 2000). These sites can be interpreted as representing single deposition events (Stein et al. 2003:313), although there is limited evidence on which to base these interpretations.

In the last 2000 years, shell mounds emerged as a conspicuous feature of the archaeological landscape across northern Australia (Ulm 2011). Over 500 mounds occur on mangrove-lined estuaries in the Weipa area alone, with the largest in excess of 12 m high, although most are less than 1 m (Bailey 1994; Morrison 2010, 2013). All mounds investigated in the southern Gulf of Carpentaria (Robins et al. 1998; Rosendahl 2012; Rosendahl et al. 2014), Weipa (Bailey 1999) and Princess Charlotte Bay (Beaton 1985) are dominated by the cockle *Anadara granosa,* which comprises more than 95% of the shell weight, with lower representation of mangrove-associated gastropods (*Telescopium* sp., *Terebralia* sp.) and bivalves (*Polymesoda* sp.), as well as occasional fish and terrestrial animal bones and stone artefacts. For Princess Charlotte Bay, Haberle and David (2004:172) linked the appearance of shell mounds to the emergence of new centralised consumption places, with associated novel foraging and disposal practices. Although there are earlier examples, the proliferation of shell mounds is associated with marked increases in the number of sites in the late Holocene (Ulm 2013; Ulm and Reid 2000; Williams et al. 2010) which are interpreted as implying higher populations (Williams 2013).

To date, studies of Australian archaeological shell deposits have focused on macroscopic faunal remains (e.g. Faulkner 2013; Ulm 2006), rather than microscopic remains (cf. Rosendahl et al. 2007). Yet, despite a range of basic sedimentary analyses being routinely applied to rockshelter deposits, rarely have Australian researchers focused a similar level of attention towards the sedimentary matrices of shell matrix sites (but see Hughes and Djohadze 1980 for an exception), especially with regards to geophysical applications such as magnetic susceptibility (Lowe 2012; Marwick 2005). In this paper, we present magnetic susceptibility and other geoarchaeological data, to explore issues of formation processes of three small shell mounds from the Gulf of Carpentaria. The results demonstrate that integrating geophysics with other techniques is an effective means by which to test previous interpretations of shell mound occupation and deposition. Further it highlights the importance in using such analyses to understand human occupation and settlement patterns in this region.

The three study sites, Guttapercha, Munburlda and Mala Katha, are located in the Gulf of Carpentaria, an epicontinental sea situated between northern Australia and Papua New Guinea containing numerous offshore islands and archipelagos, of which the Wellesley Islands Group is but one (Figure 6.1). Comprising more than 23 islands, the Wellesleys are dominated by Mornington Island, covering 966.5 km^2. With the exception of a few low elevation (<40 m) 'cliffs', where the lateritic plateau meets the coastline, the majority of the coastline is low-lying and characterised by beaches, vast supra-tidal mudflats (saltpans), beach ridges, cheniers and aeolian dunes. The main river channels tend to approach the coast fairly directly and are circumscribed by the supra-tidal hypersaline mudflats. The Sandalwood River catchment, or Yiinkan Embayment, the location of the mounds discussed in this study, is the largest drainage system on the northern Mornington coastline (Figure 6.2).

The Yiinkan Embayment comprises mostly sandy red/yellow light textured earths overlying clay or weathered lateritic Mornington bedrock, with numerous swamps and swales on the northern side of the embayment that support heavier clay and loam-rich soils (Grimes and Sweet 1979). Characterised by saltpan and mangrove-fringed tributaries and estuaries (including the Sandalwood River), the embayment is adjacent to a rich marine environment. Sandy quartz residuals formed on laterite or beach rock platforms dot the saltpan, acting as sediment traps for catching sands and silts during seasonal strong south-easterly winds; otherwise the terrain is flat.

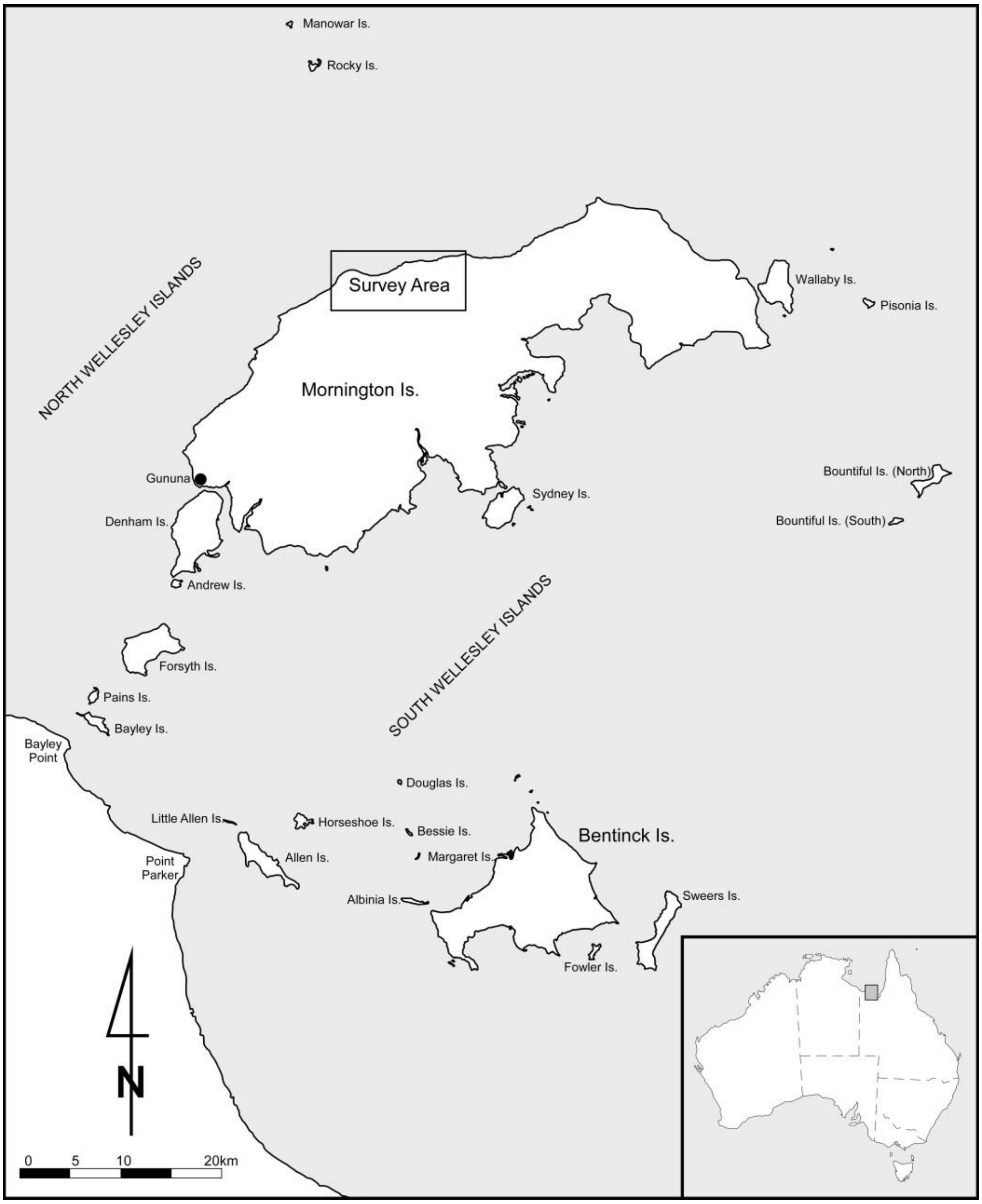

Figure 6.1 **Map showing the Wellesley Islands in the Gulf of Carpentaria, northern Australia. Study area defined by box.**

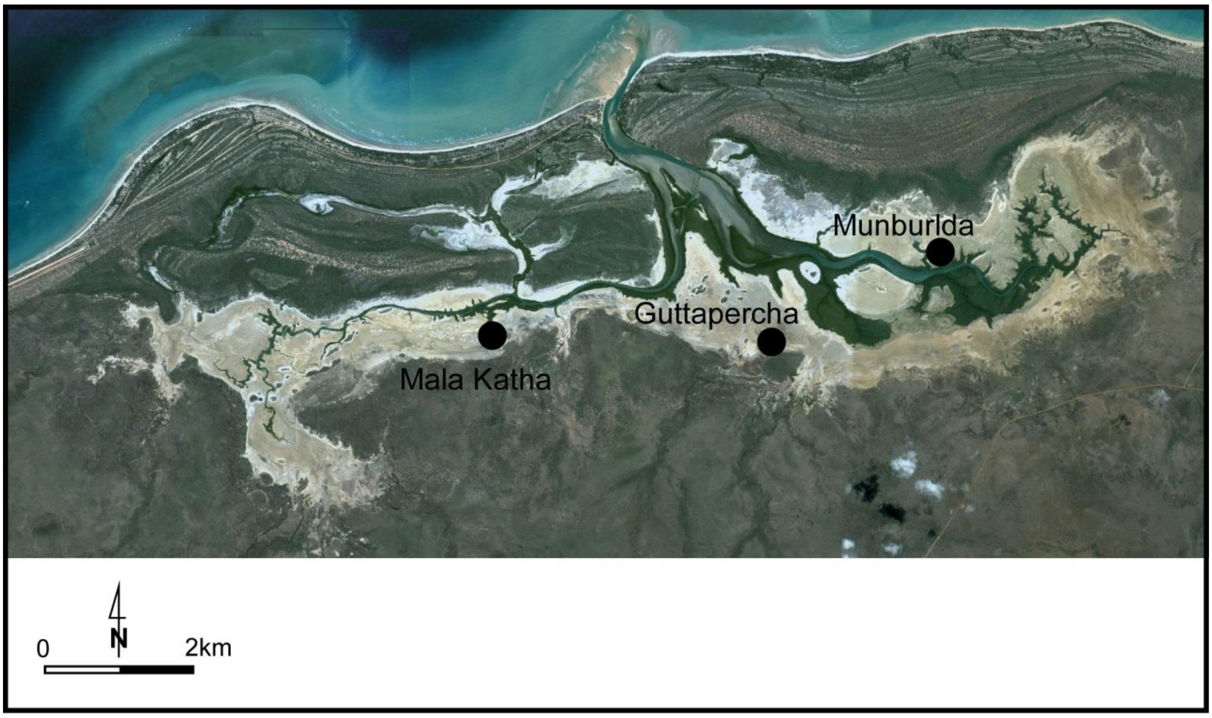

Figure 6.2 **Yiinkan Embayment showing location of the three mound sites subject to this study (image sourced from Google™ earth.**

6.3 Methods

Magnetic susceptibility measures the ease with which a material can be magnetised in the presence of a magnetic field (Thompson and Oldfield 1986:25). It detects the magnetic minerals present in sediments making it an important proxy in archaeological studies (Dalan and Banerjee 1998; Evans and Heller 2003; Long et al. 1998). Sediment magnetic susceptibility can be raised through processes such as burning (both natural and cultural), weathering or pedogenesis, whereby organics introduced to a site are subsequently ingested along with sediments by microorganisms whose excretions cause the sediment susceptibility to increase (Fassbinder et al. 1990; Le Borgne 1955; Maher 1986; Tite and Mullins 1971).

While it has been predominantly used to identify sediment features and burnt material, and to define buried cultural layers (Fassbinder and Stanjek 1993; Dalan and Banerjee 1998; Gedye et al. 2000), Dalan (2008) described the broader potential of magnetic susceptibility studies in archaeology. Since the susceptibility signal is influenced by soil development, it has been shown to also provide a means for investigating soil formation factors and in turn site formation processes, including transition from the parent material, climate, topography, relief, living organisms (micro- or macro-) and time (Evans and Heller 2003; Thompson and Oldfield 1986). Therefore, assessing soil development through magnetic methods can potentially provide information on human impacts and how site features form and change, revealing variation in sediment input from cultural or natural processes (cf. Dalan 2008; Ellwood et al. 2004; Herries 2006; Linford et al. 2005).

The application of geophysical techniques to shell mounds only began in the last decade, and such approaches focused initially on the ability of instruments (especially GPR) to map the spatial layout or extent of shell midden features, or the depth of the shell deposits (Rodrigues et al. 2009; Santos et al. 2009; Thompson et al. 2004). To date, there are very few studies documented on the magnetic susceptibility of shell mound deposits (see Connah et al. 1976) and a reason for this may be due to their complex stratigraphy (Stein et al. 2003). While magnetic susceptibility studies on other types of open sites are common (see Connah et al. 1976 and references within), the lack of magnetic susceptibility studies on shell mounds is worth noting, especially because of the potential of this technique to provide information on depositional events.

Twenty-five shell mounds were recorded on the 21 km² hyper-saline mudflats of the Yinka Embayment, three of which—Guttapercha, Mala Katha and Munburlda—were chosen for detailed recording and sampling. All three sites were subject to some form of irregular supra-tidal inundation, with Mala Katha and Munburlda being completely submerged at times by seasonal king tides boosted by wet season run-off. A 1 m² test-pit was excavated at the Guttapercha site, while 50 cm square test-pits were excavated at each of the other sites using standard archaeological techniques detailed in Rosendahl (2012) (Figure 6.2). Excavation comprised small arbitrary excavation units (XUs or spits) averaging 2.8 cm in thickness within stratigraphic units. All three sites are subject to some form of irregular supra-tidal inundation, with Mala Katha and Munburlda being completely submerged at times by seasonal king tides boosted by wet season run-off. Radiocarbon ages for all sites were calibrated using OxCal 4.1.3 (Bronk Ramsey 2009) and the Marine13 dataset (Reimer et al. 2013), with a ΔR of -49±102 for marine samples (Ulm et al. in press). All calibrated ages are reported at the 95.4% age range. Details of the stratigraphy of each site are presented in Table 6.1 and radiocarbon ages in Table 6.2.

Sediments were described according to grain size, shape and roundness (after Briggs 1977). Approximately 2 g of the bulk sediment samples collected from each XU at each site were examined to quantify the presence of fine sands, silts and clays using a Beckman & Coulter, Multisizer™ 3 Coulter Counter. Samples were screened through a 1 mm sieve, underwent heating at 12 hours in a muffle furnace at 450ºC for the determination of organic values, and were then quartered randomly. In order to mitigate potential aggregation of sediments, 100–50 ml of ISOTON II (an ionic diluent) was added to each sample, which was then subject to disaggregation in an ultrasonic bath. Sediments were suspended in solution using a magnetic stirrer, and an aliquot of approximately 10 ml was drawn up and then wet-sieved through a 355 µm mesh. Additional ISOTON II was added to achieve a solution concentration of 5–10% before processing for 20 seconds through the Multisizer using a 560 µm aperture tube (which measures 2–60% of the aperture size). Particle range distribution was established by sieving 20 g of sediment through a series of nested Endecotts sieves with parameters at coarse sand (CS) (1 mm–500 µm), medium sand (MS) (<500–250 µm) and very fine sand to silt (VFS-Si) (<125 µm).

Table 6.1 Stratigraphic unit description

Site	**Depth (cm)**	**Stratigraphic Unit (SU)**	**Description**
Guttapercha	0–31	SUI	Reddish brown (5YR 4/4) poorly sorted, subangular medium sand. Dark brown (7.5YR 3/4) at unit base. pH ranges from 8.5–9.
	31–51	SUII	Brown (10YR 4/3) to dark yellowish brown (10YR 4/6) poorly to medium sorted, subangular medium sand. Subrounded, fine sands from 27–46 cm. pH ranges from 8.5–9.
	51–120	SUIII	Culturally sterile mudflat with frequent small articulated bivalves including *Tellina* sp. and *Gafrarium* sp., all preserved *in situ* growth position. Yellowish brown (10YR 5/6) subrounded, poorly sorted coarse to fine sand. pH ranges from 8–8.5.
Mala Katha	0–22	SUI	Brown (10YR 4/3) poorly sorted, subangular medium to fine sand in upper 17 cm, shifting to poorly sorted, fine sand. Dark yellowish brown (10YR 4/4) at unit base. pH ranges from 8.5–9.5.
	22–38	SUII	Culturally sterile. Dark yellowish brown (10YR 4/4) poorly sorted, subangular fine sand. Yellowish brown (10YR 5/6) at unit base. pH was 9 near unit top, 8.5 at base.
Munburlda	0–26	SUI	Brown (7.5 YR 4/2) to dark greyish brown (10YR 4/2) well-rounded, fine silty clay. Brown (10YR 4/3) at unit base. Dense charcoal stain at 13 cm. pH ranges from 8.5–10.
	26–40	SUII	Culturally sterile clay-mudflat with numerous articulated bivalves (*Tellina* sp.), *in situ* growth position. Brown (10YR 4/3) to dark yellowish brown (10YR 4/6) well-rounded, fine silty clay. pH ranges from 8.5–9.

Other subsamples of each bulk sediment sample were packed into non-magnetic Althor P-15 boxes (5.28 cc volume) and measured using a Bartington Instruments Ltd MS3 Magnetic Susceptibility Meter with an MS2B Dual Frequency (460 and 4600 Hz) lab sensor. Repeat measurements were taken at a 0.1 range for each sample and averaged. Both low field mass (χ) and volume (SI) susceptibility measurements were taken, as well as frequency dependence of susceptibility.

Frequency dependence is the difference between the measured magnetic susceptibilities of a sediment at low and high frequency, and is expressed as a relative loss of susceptibility (χfd = (χ460Hz-χ4600Hz), or a percentage loss of the low frequency value (χfd% = (χ460Hz-χ4600Hz/χ460Hz*100) (Dearing et al. 1996; Maher 1986). In practice, this measurement shows the volume of ultrafine ferrimagnetic grains (i.e. magnetite or maghemite) known as superparamagnetic (SP) (Dalan and Banerjee 1998; Dearing et al. 1996; Maher 1986). Increases in χ in conjunction with χfd% indicate an increase in the percentage of SP grains, which are often found in burned or developed surface soils. To avoid erroneous χfd% values produced by instrument drift, a procedure of zeroing between each measurement was used. Since a magnetic field is being created for each measurement, the instrument was zeroed between each reading to calculate magnetic susceptibility.

Table 6.2 Radiocarbon dates. ~ = AMS.

Site	Depth (cm)	Stratigraphic unit (SU)	Sample material	Lab no.	14C Age	Calibrated age BP (95.4% probability)
Guttapercha	2.9	SUI	*Anadara antiquata*	Wk-23122	2015 ± 38	1376–1885
	22.5	SUI	*Anadara antiquata*	Wk-30543	1959 ± 39	1325–1823
	46.2	SUII	*Anadara antiquata*	Wk-23123	2459 ± 49	1875–2449
	52.8	SUIII	*Tellina sp.*	Wk-23124	4124 ± 30	3938–4526
Mala Katha	3.3-6.2	SUI	*Polymesoda (Geloina) coaxans*	Wk-23125	876 ± 36	315–684
	20	SUI	*Polymesoda (Geloina) coaxans*	Wk-23126	1266 ± 37	654–1087
Munburlda	0-18	SUI	*Anadara antiquata*	Wk-23127	1337 ± 34	708–1169
	22.2-24	SUI	*Anadara antiquata*	Wk-23128	1484 ± 37	868–1299

Following methods outlined in Rosendahl et al. (2007), foraminiferal analysis was carried out on sediments from selected XUs within each stratigraphic unit to assess the integrity of deposits. A 10 g subsample of the bulk sediment was wet-sieved through 2 mm, 1 mm, 850 µm, 600 µm, 500 µm, 425 µm, 250 µm and 125 µm nested Endecotts sieves. For analysis, each sieved sediment fraction was transferred to a glass petrie dish and systematically examined along transects using a JNOEC stereo XTX-5 series C-type incident light binocular microscope. Identification of foraminifera and their habitats was assisted by reference to published texts (Albani 1979; Militante-Matias 1990; Murray 1991; Palmieri 1976; Sen Gupta 1999) and the online World Modern Foraminifera Database (Hayward 2013). Each foraminifera taxon was quantified by establishing the minimum number of individuals (MNI) based on counts of the umbilical phenotype. To facilitate comparison of the analysed sediments, densities are reported as the number of foraminifera per 100 g of sediment.

All excavated deposits were dry-sieved through 2.1 mm sieves in the field and brought back to the laboratory for sorting. Stone artefacts recovered from each excavation unit were analysed noting raw material type, length, width and height (see Rosendahl 2012). Other material collected and analysed included shell artefacts or worked shell, wood charcoal, fish bone, and shell (marine and bivalve). These criteria were also used to help distinguish the cultural origins of the mounds (after Attenbrow 1992:4; Gill et al. 1991:335; Rosendahl et al. 2007; Ulm 2006).

6.4 Results

6.4.1 Guttapercha

The largest mound recorded on the Sandalwood River saltpan, Guttapercha has a diameter of 25 m and rises ~1 m above the surrounding land surface (Figure 6.3). The surface of the mound exhibited a high density scatter of large estuarine gastropods dominated by *Terebralia* spp. and *Telescopium telescopium*, with some bivalves including *Polymesoda coaxans*, *Anadara antiquata* (cockle shell) and *Gafrarium* sp., and a small number of stone artefacts.

Figure 6.3 Guttapercha shell mound, context image.

As summarised in Table 6.1, excavation revealed three stratigraphic units (SU), with cultural materials including shell, stone artefacts, fish bone and charcoal present in both SUI and SUII (Figures 6.4 and 6.5). Culturally sterile sediments were encountered in SUIII at a depth of 51 cm below mound surface, incorporated into which were articulated *Tellina* sp. shells in growth position which returned an age of 3938–4526 cal BP (Wk-23124; see Table 6.2), indicating the saltpan had developed by that time. Samples of *A. antiquata* from 2.9, 22.5 and 46.2 cm below surface produced radiocarbon ages of 1376–1885 cal BP (Wk-23122) (SUI), 1325–1823 cal BP (Wk-30543) (SUI) and 1875–2449 cal BP (Wk-23123) (SUII), respectively (Table 2). There was no visible evidence of any hiatuses in the sequence, i.e. culturally sterile layers such as dark soil or sand horizons as observed elsewhere (Morrison 2010, 2013).

The radiocarbon ages indicate the cultural deposits at Guttapercha were deposited between ~1600 and ~2200 cal BP. Given that the underlying saltpan sediments were in place by ~4200 cal BP, this site was therefore first occupied some 2000 years after the last major phase of local landform development. The uppermost stratigraphic unit (SUI), comprising the densest cultural material, accumulated rapidly in less than 100 years, approximately 1600 years ago, with no stratigraphic evidence for separate depositional events occurring during that time.

Sediment size analysis demonstrated the majority of sediments (50% or greater) throughout the Guttapercha deposit are very fine quartz sands and silts, indicating a consistent seasonal aeolian sediment supply to the site (Figure 6.4). Analysis of the silt-sized particles (62.5–7.8 µm) showed a consistent 70% in the coarse silt range.

As shown in Figure 6.5, magnetic susceptibility analysis revealed several increases in χ in the upper, central and lower XUs of SUI, while values were consistently lower in SUII and SUIII. A slight increase in the basal unit (taken from an auger core that allowed the sampling of sediments at a depth lower than that achieved in the excavation itself) is likely to be a natural signal driven by *in situ* decay of ironstone in the sediment matrix. The higher χ values in the upper and lower XUs of SUI correspond well with similar increases in stone artefacts, wood charcoal, fish bone and shell. The frequency dependence of susceptibility also increases at Guttapercha only in the upper and lower XUs of SUI, directly below the interface between SUI and SUII, and at the interface between SUII and SUIII. There are also slight increases in the central XUs of both SUII and SUIII. The lower χ and χfd% in SUII and SUIII correspond with increases in very fine sands and silts, and decreases in artefactual material.

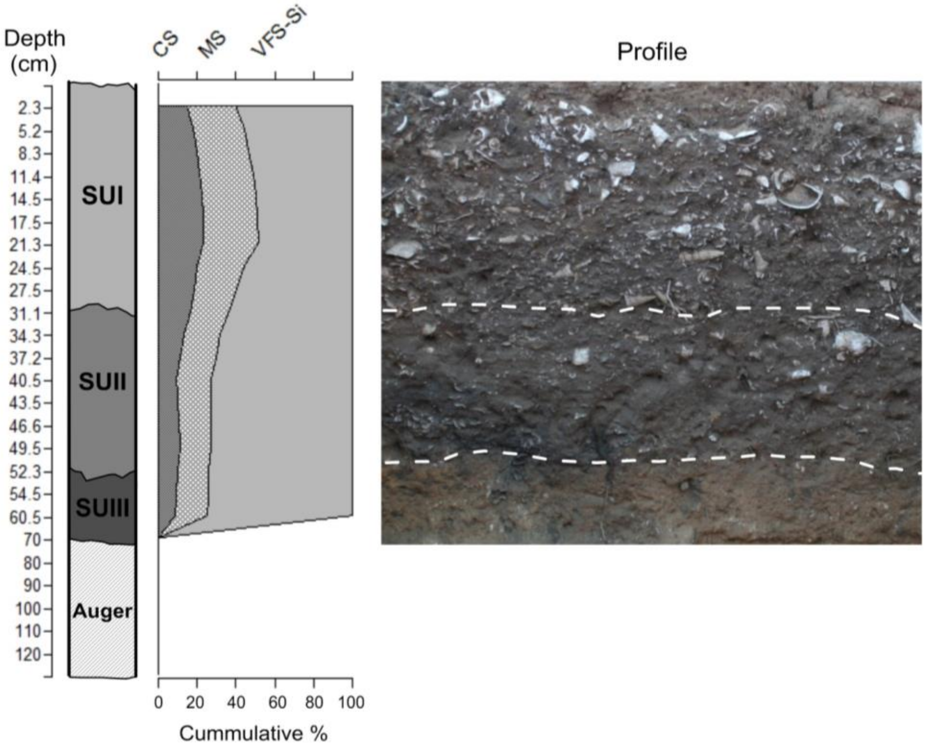

Figure 6.4 **Sediment profile and particle size distribution of Guttapercha. Note that samples below 60 cm were augered beyond the base of the excavation. CS=coarse sands; MS=medium sands; VFS-Si=very fine sands and silts.**

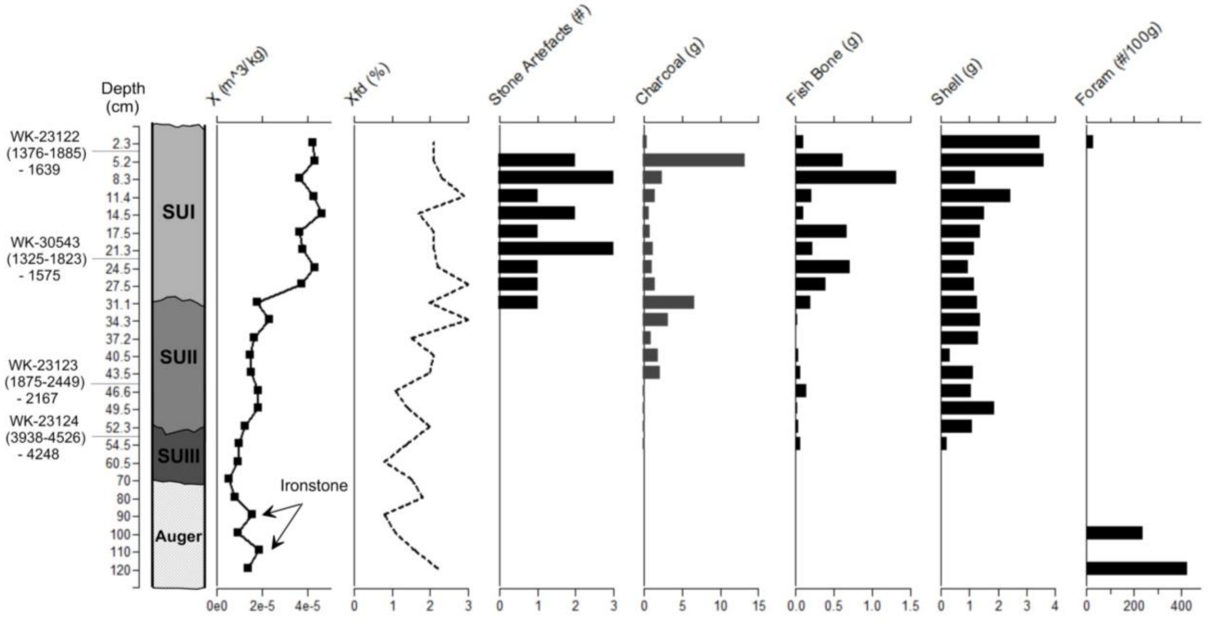

Figure 6.5 **Combined archaeological, geoarchaeological and geophysical data at Guttapercha.**

The only correlation where we see an increase in both χ and χfd% is directly below the interface between SUI and SUII, indicating a change in the fine-grained component of magnetic grains at this depth which could represent a developed surface. Since all increasing χ values in SUI do not have a corresponding increase in χfd%, it is apparent that magnetic enhancement is not a result of the presence of fine-grained ferrimagnetics. Sediment size analysis reveals that as χ increases, so too do the medium-coarse sands. This suggests that a depositional processes largely involving humans account for these magnetic variations, as we would expect archaeological materials to lie in the coarse fraction textural size. A bivariate plot (Figure 6.6) of χ to χfd% provides information on the relationships between the two parameters and the proportion of fine SP grains. For Guttapercha, the χfd% is between 0.77–3.05%, suggesting that the sediments are low in SP grains (cf. Dearing et al. 1996). These low percentages overall likely reflect young soils, since it has been shown elsewhere that young soils have low percentages in χfd% (Dalan 2006; Dearing et al. 1996).

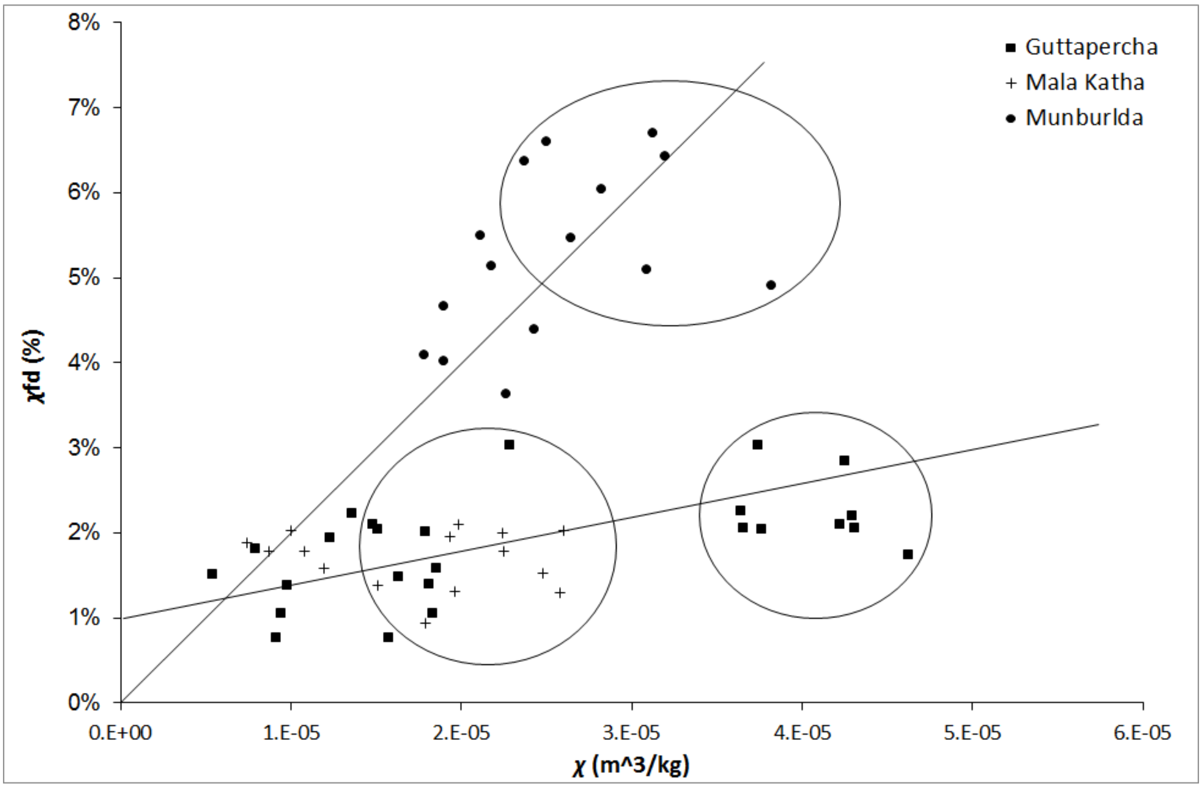

Figure 6.6 **Bivariate plot showing the relationship between χ with χfd% for Guttapercha, Munburlda and Mala Katha. Circled data represent SUI and SUII.**

Foraminiferal analysis was carried out on sediment samples from XUs 2, 5, 8, 11, 17, 20 and three SUIII samples collected by auger (Figure 6.5). In total, two (25/100 g) foraminifera were identified in XU2 (2.3 cm below surface), with 26 (233/100 g) and 52 (422/100 g) in two of the auger samples (those taken at 100 cm and 120 cm, respectively); no foraminifera were identified in the other examined samples. Foraminifera density in the SUIII samples is well below that expected for high energy/wave deposited natural units of >1000/100 g, such as were recorded for chenier deposits on the central Queensland coast, but still well above the parameters established for cultural coastal deposits (Rosendahl et al. 2007). Coupled with the sediment size analysis and abundance of pisoliths formed through episodic saturation, the foraminiferal concentration reveals low energy tidal deposition in SUIII (i.e. below the cultural deposits), as opposed to a high energy wave-deposited concentration, with no evidence for post-depositional marine disturbance of the cultural deposits of the mound excepting low-energy seasonal inundation. Individual foraminifera were too eroded to allow identification to taxon level.

6.4.2 Munburlda

Munburlda is one shell mound amongst a cluster of such sites along the eastern branch of the Sandalwood River. Rising 45 cm above the surrounding substrate, it had a diameter of 10 m. Surface inspection gave the impression it was dominated by *A. antiquata*; however, excavation revealed co-dominance between the latter and *Saccostrea glomerata* (oyster). Other marine shell taxa present included the bivalves *Isognomon* sp. and *Marcia hiantina*, and gastropods *Terebralia* spp., *Telescopium telescopium*, *Melo amphora* (baler) and *Syrinx aruanus* (trumpet shell). Like Guttapercha, a small number of stone artefacts were observed on the surface.

Excavation revealed two stratigraphic units: SUI, an upper shell-rich cultural deposit which includes shell, fish bone, stone artefacts and charcoal, and SUII, a lower culturally sterile mudflat commencing at 26 cm below surface (Figure 6.7 and Table 6.1). Again, incorporated into the base of SUII were articulated *Tellina* sp. shells in growth position. Samples of *A. antiquata* from 0–1.8 and 22.2–24 cm below surface revealed a period of shell deposition lasting ~150 years, between 708–1169 and 868–1299 cal BP (Wk-23127 and Wk-23128, respectively; see Table 6.2).

Sediment analysis clearly illustrates an altered sediment supply between the lower saltpan unit (SUII) and the upper cultural unit (SUI) (Figure 6.7). The percentage of sediments comprising very fine quartz sands and silts was 40% in SUI, doubling to 80% in SUII. Multisizer results indicate no obvious change in the silt fraction, with 75% of grains falling within the medium silt range throughout the deposit. This suggests a relatively continuous deposition of sediments from low energy supra-tidal activity throughout the sequence, with the commencement of aeolian sedimentation in SUI as the build-up of shells started to act as a sediment trap.

The magnetic susceptibility results revealed increases in χ only in the upper XUs of SUI, which corresponded with increases in stone artefacts, fish bone, shell and, in particular, wood charcoal (Figure 6.8). As with Guttapercha, the values were lower in SUII and corresponded to increases in very fine sands and silts. With the exception of shell, both artefactual material and χ values decrease with depth; alternatively, shell increases slightly before dropping off in SUII. The frequency dependence of susceptibility increased only in the central and lower XUs of SUI and in the central portions of SUII. These values decrease slightly at the interface between SUI and SUII with a change in sediment.

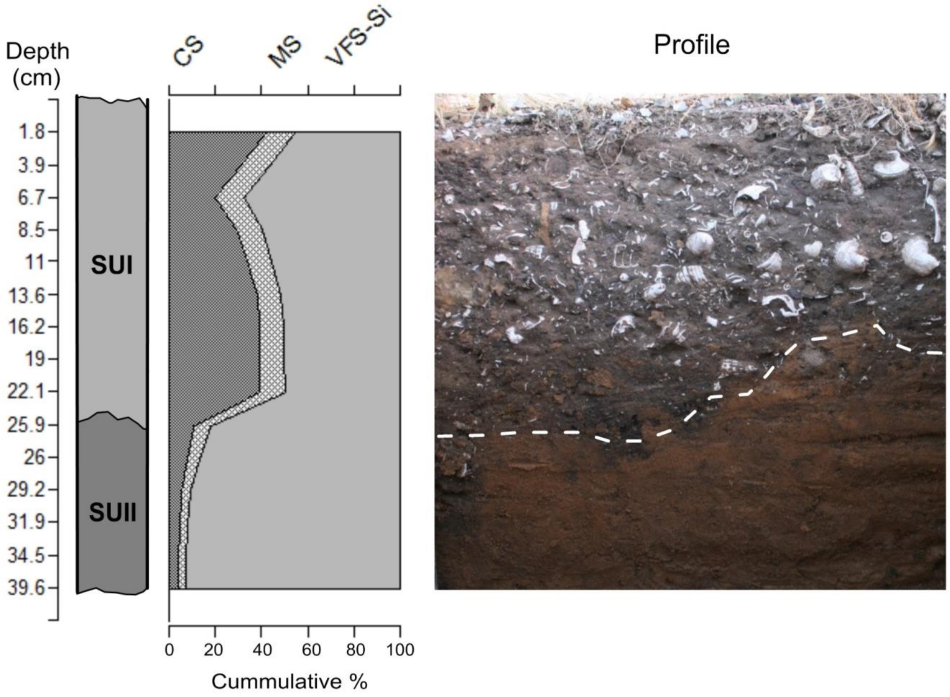

Figure 6.7 Sediment profile and particle size distribution of Munburlda, Square A.

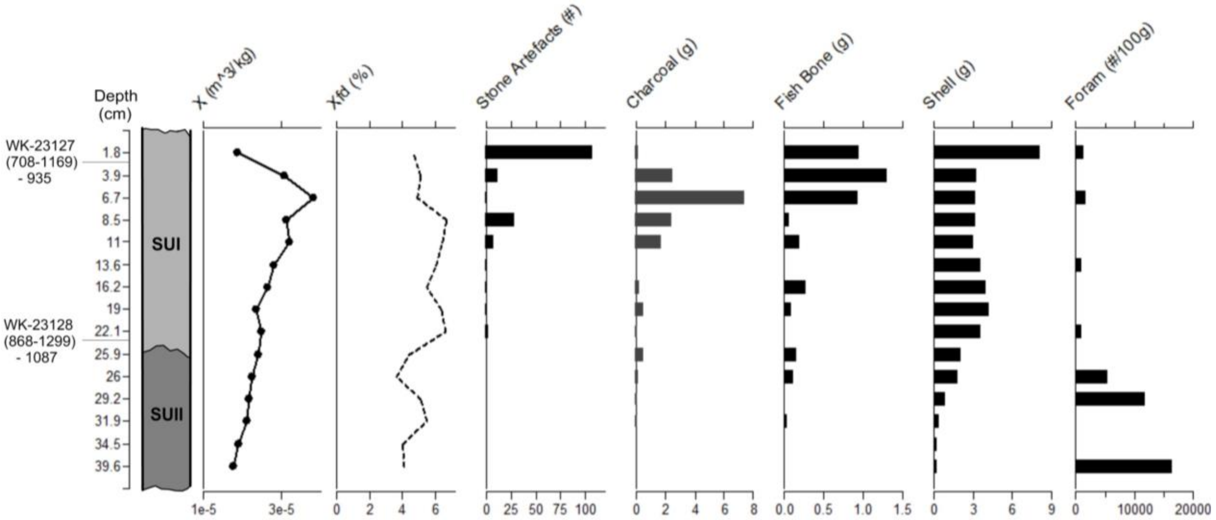

Figure 6.8 Combined geoarchaeological and geophysical data at Munburlda.

There is no positive correlation between χ and χfd% at Munburlda. Instead, where χ increases we see the opposite, i.e. a decrease in χfd%, demonstrating that magnetic enhancement is not a result of the presence of fine-grained ferrimagnetics. The sediment size analyses revealed that the increase in χ near the upper XUs of SUI corresponded closely with an increase in very fine sands and silts, and not in medium-coarse sands as was the case at Guttapercha. While these increases are largely a result of anthropogenic inputs (since artefactual material increases are evident), the changes in textural size could reflect an accumulation of either aeolian or alluvial sediments that may have overprinted the archaeological material. Further analysis of the magnetic minerals themselves is required to determine this. The bivariate plot shows that Munburlda's sediments range in χfd% between 3.65–6.79% and trend more towards χfd% than χ, suggesting a greater proportion of SP grains in the assemblage, but overall lower concentrations of SP grains in general (see Figure 6.6).

Foraminiferal analysis was carried out on XUs 1, 3A, 6, 9, 10, 12 and 15A, with a total of 1027 foraminifera identified in across all XUs (Figure 6.8). The cultural XUs of SUI (0–26 cm) exhibited a density of <1600/100 g, with the lower SUII (26–40 cm) exhibiting a density >10,000/100 g with XU10 representing a mixed unit with a foraminifera density of 5240/100 g. The overall assemblage is indicative of a supra-tidal estuarine zone as determined by the abundance of *Quinqueloculina* spp., including *Q. seminula*, along with *Elphidium hughesi* (Wang and Chappell 2001).

6.4.3 Mala Katha

Mala Katha, the smallest of the excavated shell mounds recorded on Mornington Island, measured 13 by 5 m and rose ~37 cm above the surrounding substrate. It is situated along the southern margin of the saltpan, in the vicinity of several other shell mounds and bioherms. The surface of the mound exhibited a high density marine shell scatter dominated by *Polymesoda coaxans*, *Terebralia* spp. and *Telescopium telescopium*. *Anadara antiquata* and *Gafrarium* sp. were also present in small quantities, along with a small number of stone artefacts.

Again, two stratigraphic units were present: an upper, homogenous cultural unit including shell, fish bone and charcoal to 22 cm below surface (SUI), and culturally sterile sediments (SUII) beneath 22 cm (Figure 6.9 and Table 6.1). Two samples of *P. coaxans* from 3.3–6.2 and 20 cm, produced radiocarbon determinations of 315–684 and 654–1087 cal BP (Wk-23125 and Wk-23126, respectively; see Table 6.2), indicating that Mala Katha accumulated between ~800 and 500 cal BP.

Sediment analyses demonstrate a demarcation between the stratigraphic units, with SUI containing higher percentages of medium to coarse sands than SUII, which is dominated by very fine sands and silts (<80%) (Figure 6.9). The decrease in very fine sands in SUII moving up into SUI, likely shows the shell mound acting as a sediment trap accumulating larger sands. Multisizer results show no obvious change in the proportions of coarse, medium and fine silts, with SUI sediments exhibiting 90% of grains <42 µm and SUII sediments exhibiting 90% <41 µm. The particle size range present identifies the presence of both wind-borne sands and water-deposited silts, and suggests relatively consistent low energy water deposition with an increase in aeolian sedimentation in SUI.

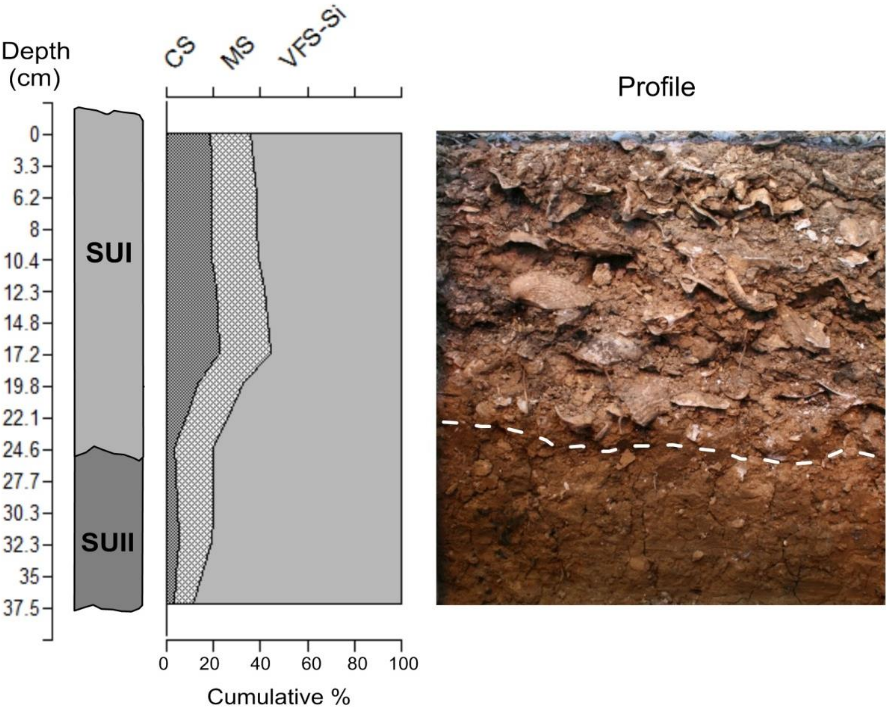

Figure 6.9 Sediment profile and particle size distribution of Mala Katha.

As shown in Figure 6.10, the magnetic susceptibility analysis revealed several χ increases in the upper, central and lower XUs of SUI. Again, values were lower in SUII and correspond to increases in very fine sands and silts; as χ increases so does the coarse fraction. The higher χ values in the central to lower XUs of SUI corresponds closely with increases in stone artefacts, wood charcoal, fish bone and shell. These values were associated with a high level of charred shells in the deposit, which were associated with soil staining observed during excavation. The χ increases in the upper XUs of SUI corresponded only to increases in fish bone and shell, while the χ increase at the bottom of SUI corresponded only to an increase in very fine sands and silts. All the frequency dependence of susceptibility increases occur in SUI, although for SUII, χfd percentages are generally high with depth.

The correlating increases in both χ and χfd% in SUI indicate that there is a slight increase in the fine-grained component of magnetic grains within this unit. While some artefactual material is present in the upper XUs of SUI, the slight decrease in medium-coarse sands and increase in both χ and χfd% could indicate a developed surface (e.g. pedogenesis) or sediment change. The χ increases that occur directly below this represents changes to the anthropogenic inputs. This is supported by increases in quantities of artefactual material and the soil staining. The higher χfd% and low χ values in SUII are likely derivative of sediment changes (increase in very fine sands and silts). Like Guttapercha, the χfd% of Mala Katha's sediments are low, ranging between 0.94–2.11%. This demonstrates that the sediments are low in SP grains and again may reflect young soils (see Figure 6.6). Although SP grains give a higher χ, all the site's sediments have similar χ values despite Guttapercha and Mala Katha having lower χfd%. This indicates that ferrimagnetic concentrations are lower in those two sites. Foraminifera analysis was carried out on samples from XUs 2, 5, 8, 11, 14 and 16 (Figure 6.10) with very low densities recovered. Two foraminifera (26/100 g) were recovered from XU5 (10.48 cm), and 1 (12/100 g) from XU8 (17.2 cm). No foraminifera were recovered from the SUII sediments.

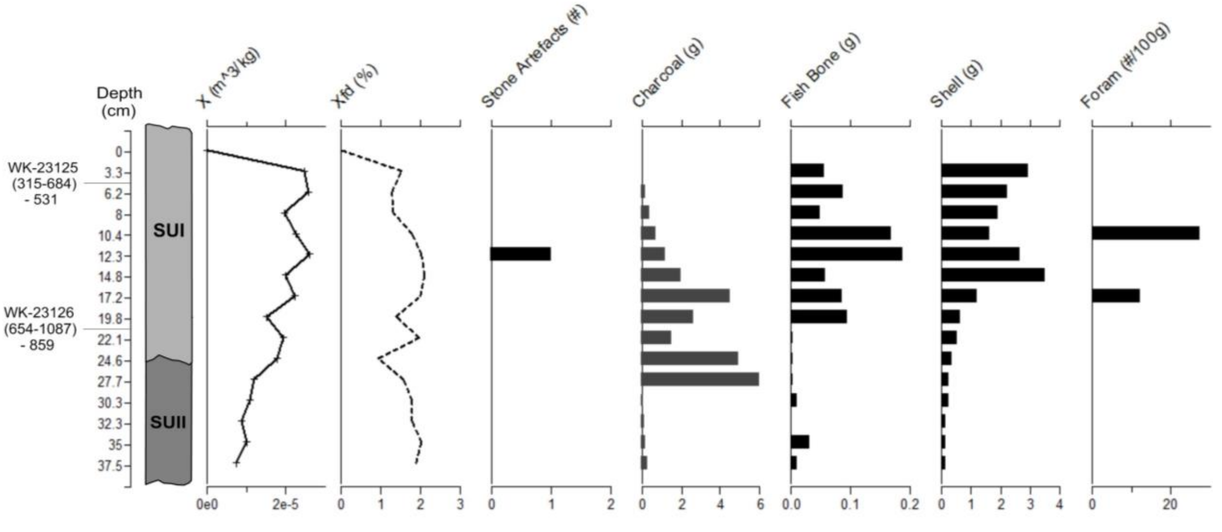

Figure 6.10 Combined geoarchaeological and geophysical data at Mala Katha.

6.5 Discussion

There is a strong relationship between depositional processes and magnetic properties at all three shell mound sites in the Yinkan Embayment. Artefact-rich deposits should logically have a higher magnetic susceptibility than sterile deposits due to their having either a higher organic content (associated with by bacterial microorganisms) or burned sediments resulting from either cultural or natural fires on the three shell mounds. However, natural pedogenesis can also cause an enhanced susceptibility signal (Dalan 2008; Evans and Heller 2003).

It is clear that the observed magnetic enhancement is related to several factors. Positive correlations with artefactual material were the best proxy for determining magnetic variations that were more likely anthropogenic in origin than natural. Correlations with changes in grain sizes indicated that some of the increased magnetic values could result from changes in sediment sources (e.g. aeolian or alluvial). Where we see increases in both χ and χfd% indicate increases in the fine grained component of the sediments, which would reflect either pedogenesis or burning (natural or cultural), however weathering processes may also account for this.

There were changes apparent within stratigraphic units, particularly those units containing the abundance of archaeological materials (e.g. stone artefacts, fish bone, wood charcoal and shell). There tended to be a general distinction not only in colour between stratigraphic units, but also changes in sediment size (often with increasing medium to coarse sands rising upwards through the profiles) and susceptibility values. Overall, these observations suggest that the sites retain a high degree of integrity.

Correlations between increases in χ in conjunction with χfd%, as indicators of either cultural (burned) or natural (well-developed soils) inputs, were apparent at Guttapercha and Mala Katha. Changes in artefactual and sediment size data correlated with increased susceptibility values were the best indicators of human occupation, demonstrating that fine-grained magnetic grains are not responsible for the increase in susceptibility (we had initially anticipated that increased susceptibility values might be the result of the presence of larger magnetic grains).

From the integrated data sets, we can infer that both Guttapercha and Mala Katha showed repeated occupation within their uppermost stratigraphic units. This is confirmed by increases in magnetic susceptibility values and quantities of fish, artefactual stone, wood charcoal and shell (Rosendahl 2012). Given the available data, it is difficult to determine that multiple occupations events had occurred at Munburlda based solely on the susceptibility data. Despite low χ values at the bottom of SU1, the presence of artefactual material and increases in the coarse fraction of the sediments indicates the onset of human occupation.

In the study area, McKnight (1999:89) noted that ‘shellfish were consumed during the rainy season, when the tides were exceptionally high’. He specifically noted that the Yinkan Embayment was a place where shell was ‘consumed’, rather than where people camped. This proposal was supported by oral testimony provided by Cyril Moon, Lardil elder (pers. comm., June 2013). Elsewhere, Lowe and Fogel (2010:250) observed episodic deposition in ditch fill in the Northern Plains of North America using magnetic susceptibility. They found that high χ values correspond to occupational layers and low χ values correspond to windblown culturally sterile in-fill. While we see a similar χ trend at Guttapercha and Mala Katha (increases in χ followed by abrupt decreases), based on the available data it is difficult to ascertain the rate and periodicity of visitation.

Further research examining the magnetic variations associated with anthropogenic inputs and sediment changes using other magnetic parameters would enhance the results. It would also be productive to investigate whether anthropogenic inputs are being overprinted by other sediment sources and if episodic deposition is taking place using micromorphology and x-ray diffraction (XRD). One thing is clear; however, people used these mounds more than once resulting in discrete deposition events that are apparent in the sedimentary and magnetic data, even though the macroscopic data suggested deposition was continuous.

6.6 Conclusion

Change as represented in the Australian archaeological record is, in most cases, subtle, with cultural change represented through nuanced changes in the subsistence economy and/or tool production, rather than through the emergence of new architectures, monuments or evidence of large-scale technological and societal change. As a consequence, archaeologists are increasingly turning to multidisciplinary approaches to maximise the amount and resolution of data obtainable, to provide a more informed understanding of the past.

Numerous studies have focused on assessing depositional processes of, and post-depositional disturbance to, Australian archaeological sites. When identifying patterns of change through time, studies of open sites tend to focus only on the macroscopic cultural materials, i.e. shells and stone artefacts, correlated with gross stratigraphic change supported by radiocarbon chronologies. The pitfalls of these approaches is that shell matrix sites typically have a homogenous stratigraphic profile with overlapping or close radiocarbon dates that denote rapid, 'archaeologically instantaneous' site formation. These factors lead to the interpretation of single event or rapid short-term deposition, or unchanging site use through time.

This pilot project has highlighted the benefits of integrating geoarchaeological approaches, including magnetic susceptibility, to help establish subtle changes in shell mounds of the Yinkan Embayment were repeatedly visited, despite radiocarbon dates suggesting effectively ‘archaeologically instantaneous’ deposition. As open sites are increasingly being relied on to establish regional chronologies and identify change through the mid- to late Holocene in Australia, it is paramount that robust techniques be implemented to characterise the complex depositional processes that contribute to the formation of these sites. This analysis improved our understanding of the depositional history of the Guttapercha and Mala Katha sites, and has important implications for studies of shell mounds elsewhere, where the limitations of radiocarbon dating precision may similarly mask multiple deposition events.

Acknowledgements

This project was supported under the Australian Research Council's Discovery Projects (project numbers DP0663047 and DP120103179). Sean Ulm is the recipient of an Australian Research Council Future Fellowship (project number FT120100656). We acknowledge the Lardil, Kaiadilt, Yangkaal and Gangalidda traditional owners of the Wellesley Islands as partners in this research project. The Gulf Region Aboriginal Corporation RNTBC and Kaiadilt Aboriginal Corporation collaborated in establishing the research framework for this project. We thank Johnny Williams and family for allowing access to their country. Thanks to Paul Memmott, Ian Lilley, Richard Robins, Errol Stock and Craig Sloss for support and advice.

References

Albani, A. D. 1979 *Recent Shallow Water Foraminifera from New South Wales.* Cronulla, NSW: Australian Marine Sciences Association.

Attenbrow, V. 1992 Shell bed or shell midden. *Australian Archaeology* 34:3–21.

Bailey, G. 1994 The Weipa shell mounds: natural or cultural? In M. Sullivan, S. Brockwell and A. Webb (eds), *Archaeology in the North: Proceedings of the 1993 Australian Archaeological Association Conference*, pp.107–129. Darwin: North Australia Research Unit, Australian National University.

Bailey, G. 1999 Shell mounds and coastal archaeology in northern Queensland. In J. Hall and I. McNiven (eds), *Australian Coastal Archaeology*, pp.105–112. Canberra: Research School of Pacific and Asian Studies, The Australian National University.

Beaton, J. 1985 Evidence for a coastal occupation time-lag at Princess Charlotte Bay (north Queensland) and implications for coastal colonisation and population growth theories for Aboriginal Australia. *Archaeology in Oceania* 20:1–20.

Briggs, D. J. 1977 *Sediments*. London: Butterworths.

Bronk Ramsey, C. 2009 Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–360.

Connah, G., P. Emmerson and J. Stanley 1976 Is there a place for the proton magnetometer in Australian field archaeology? *Mankind* 10(3):151–155.

Dalan, R. A. 2006 A geophysical approach to buried site detection using down-hole susceptibility and soil magnetic techniques. *Archaeological Prospection* 13:182–206.

Dalan, R. A. 2008 A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: Recent developments and prospects. *Archaeological Prospection* 15:1–31.

Dalan, R. A. and S. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13(1):3–36.

Dearing, J. A., K. L. Hay, S. M. J. Baban, A. S. Hudleston, E. M. H. Wellington and P. J. Loveland 1996 Magnetic susceptibility of soil: An evaluation of conflicting theories using a national data set. *Geophysics Journal International* 127:728–734.

Ellwood, B., F. B. Harrold, S. L. Benoist, P. Thacker, M. Otte, D. Bonjean, G. J. Long, A. M. Shahin, R. P. Hermann and F. Grandjean 2004 Magnetic susceptibility applied as an age-depth-climate relative dating technique using sediments from Scladina Cave, a late Pleistocene cave site in Belgium. *Journal of Archaeological Science* 31(3):283–293.

Evans, M. E. and F. Heller 2003 *Environmental Magnetism: Principles and Applications of Enviromagnetics*. London: Academic Press.

Fassbinder, J. W. E. and H. Stanjek 1993 Occurrence of bacterial magnetite in soils from archaeological sites. *Archaeology in Polona* 31:117–128.

Fassbinder, J. W. E., H. Stanjek and J. Vali 1990 Occurrence of magnetic bacteria in soil. *Nature* 343:161–163.

Faulkner, P. 2013 *Life on the Margins: An Archaeological Investigation of Late Holocene Economic Variability, Blue Mud Bay, Northern Australia*. Terra Australis 38. Canberra: ANU E Press.

Gedye, S. J., R. T. Jones, W. Tinner, B. Ammann and F. Oldfield 2000 The use of mineral magnetism in the reconstruction of fire history: A case study from Lago di Origlio, Swiss Alps. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164:101–110.

Gill, E. D., J. E. Sherwood, J. H. Cann, P. J. Coutts and C. J. Magilton 1991 Pleistocene shell beds of the Hopkins River, Warrnambool, Victoria: Estuarine sediments or Aboriginal middens? In M. Williams, P. De Decker and A.P. Kershaw (eds), *The Cainozoic in Australia: A Reappraisal of the Evidence*, pp.321–338. Special Publication 18. Sydney: Geological Society of Australia.

Grimes, K. G. and I. P. Sweet 1979 Westmoreland Queensland: 1:250,000 Geological Series Explanatory Notes. Canberra: Australian Government Publishing Service.

Haberle, S. G. and B. David 2004 Climates of change: Human dimensions of Holocene environmental change in low latitudes of the PEPII transect. *Quaternary International* 118/119:165–179.

Hayward, B. W. 2013 World Modern Foraminifera Database. Accessed 25 March 2013 at http://www.marinespecies.org/foraminifera/.

Herries, A. I. R. 2006 Archaeomagnetic evidence for climate change at Sibudu Cave. South African *Humanities* 18:131–147.

Hughes, P. J. and V. Djohadze 1980 *Radiocarbon Dates From Archaeological Sites on the South Coast of New South Wales and the Use of Depth/Age Curves. Occasional Papers in Prehistory 1*. Canberra: Department of Prehistory, The Australian National University.

Le Borgne, E. 1955 Susceptibilite magnetiqe anormale de sol superficiel. *Annales de Geophysique* 11:399–419.

Linford, N., P. Linford and E. Platzman 2005 Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames Valley, UK. *Journal of Archaeological Science* 32(7):1037–1043.

Long, C. J., C. Whitlock, P. J. Bartlein and S. H. Millspaugh 1998 A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* 28:774–787.

Lowe, K. M. 2012 Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84.

Lowe, K. M. and A. S. Fogel 2010 Understanding Northeastern Plains village sites through archaeological geophysics. *Archaeological Prospection* 17:247–257.

Maher, B. A. 1986 Characterisation of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interior* 42:76–92.

Marwick, B. 2005 Element concentrations and magnetic susceptibility of anthrosols: Indicators of prehistoric human occupation in the inland Pilbara, Western Australia. *Journal of Archaeological Science* 32:1357–1368.

McKnight, D. 1999 *Peoples, Countries, and the Rainbow Serpent: Systems of Classification among the Lardil of Mornington Island.* Oxford: Oxford University Press.

Militante-Matias, P. J. 1990 Studies on recent foraminifera from shallow water of the southeastern Manila Bay area, Philippines. In Y. Takayanagi and T. Saito (eds), *Studies in Benthonic Foraminifera: Proceedings of the Fourth International Symposium on Benthic Foraminifera*, Sendai, pp.167–174. Takai: Takai University Press.

Morrison, M. 2010 *The Shell Mounds of Albatross Bay: An Archaeological Investigation of Late Holocene Production Strategies Near Weipa, North Eastern Australia*. Unpublished PhD thesis, Department of Archaeology, Flinders University, Adelaide.

Morrison, M. 2013 From scatter to mound: A new developmental model for shell mound sites at Weipa. *Queensland Archaeological Research* 16:165–184.

Murray, J. W. 1991 *Ecology and Palaeoecology of Benthic Foraminifera*. Essex: Longman Scientific and Technical.

Palmieri, V. 1976 Modern and relict foraminifera from the central Queensland continental shelf. *Queensland Government Mining Journal* 77:407–436.

Reimer, P. J., E. Bard, A. Bayliss, J.W. Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, H. Cheng, R. L. Edwards, M. Friedrich. P. M. Grootes, T. P. Guilderson, H. Haflidason, I. Hajdas, C. Hatté, T. J. Heaton, D. L. Hoffmann, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, S. W. Manning, M. Niu, R. W. Reimer, D. A. Richards, E. M. Scott, J. R. Southon, R. A. Staff, C. S. M. Turney and J. van der Plicht 2013 INTCAL13 and MARINE13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–1887.

Robins, R. P., E. C. Stock and D. S. Trigger 1998. *Saltwater people, saltwater country: Geomorphological, anthropological and archaeological investigations of the coastal lands in the southern Gulf country of Queensland. Cultural Heritage Series 1.* Memoirs of the Queensland Museum 1:75–125.

Rodrigues, S. I., J. L. Porsani, V. R. N. Santos, P. A. D. Deblasis and P .C. F. Giannini 2009 GPR and inductive electromagnetic surveys applied in three coastal sambaqui (shell mounds) archaeological sites in Santa Catarina state, south Brazil. *Journal of Archaeological Science* 36:2081–2088.

Rosendahl, D., S. Ulm and M. I. Weisler 2007 Using foraminifera to distinguish between natural and cultural shell deposits in coastal eastern Australia. *Journal of Archaeological Science* 34(10):1584–1593.

Rosendahl, D. 2012 *The Way it Changes Like the Shoreline and the Sea: The Archaeology of the Sandalwood River, Mornington Island, Southeast Gulf of Carpentaria, Australia*. Unpublished PhD thesis, School of Architecture, The University of Queensland, St Lucia.

Rosendahl, D., S. Ulm, H. Tomkins and L. A. Wallis 2014 Late Holocene changes in shellfishing behaviours from the Gulf of Carpentaria, northern Australia. *Journal of Island and Coastal Archaeology* 9(2) 253–267.

Santos, V. R. N., J. L. Porsani, C. A. Mendonça, S. L. Rodrigues and P. D. DeBlasis 2009 Reduction of topography effect in inductive electromagnetic profiles: Application on coastal sambaqui (shell mound) archaeological site in Santa Catarina state, Brazil. *Journal of Archaeological Science* 36:2089–2095.

Sen Gupta, B. K. 1999 Foraminifera in marginal marine environments. In B. K. Sen Gupta (ed.), *Modern Foraminifera*, pp.141-160. London: Kluwer Academic Publishers.

Shiner, J. S., P. C. Fanning, S. J. Holdaway, F. Petchey, C. Beresford, E. Hoffman and B. Larsen 2013 Shell mounds as the basis for understanding human-environment interaction in far north Queensland, Australia. *Queensland Archaeological Research* 16:65–91.

Stein, J. K., J. N. Deo and L. S. Phillips 2003 Big sites—Short time: Accumulation rates in archaeological sites. *Journal of Archaeological Science* 30:297–316.

Thompson, R. and F. Oldfield 1986 Environmental Magnetism. London: Allen and Unwin.

Thompson, V. D., M. D. Reynolds, B. Haley, R. Jefferies, J. K. Johnson and L. Humphries 2004 The Sapelo shell ring complex: Shallow geophysics on a Georgia sea island. *Southeastern Archaeology* 23(2):192–201.

Tite, M. S. and C. Mullins 1971 Enhancement of the magnetic susceptibility of soils on archaeological sites. *Archaeometry* 13:209–219.

Ulm, S. 2006 *Coastal Themes: An Archaeology of the Southern Curtis Coast, Queensland*. Terra Australis 24. Canberra: ANU E Press.

Ulm, S. 2011 Coastal foragers on southern shores: Marine resource use in northeast Australia since the late Pleistocene. In N. F. Bicho, J. A. Haws and L. G. Davis (eds), *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement*, pp.441–461. Interdisciplinary Contributions to Archaeology. New York: Springer.

Ulm, S. 2013 ‘Complexity’ and the Australian continental narrative: Themes in the archaeology of Holocene Australia. *Quaternary International* 285:182–192.

Ulm, S., F. Petchey, G. E. Jacobsen and D. Rosendahl in press Pre-bomb marine radiocarbon reservoir variability in the eastern Gulf of Carpentaria, Queensland, Australia. *Queensland Archaeological Research* 17.

Ulm, S. and J. Reid 2000 Index of dates from archaeological sites in Queensland. *Queensland Archaeological Research* 12:1–129.

Wang, P. and J. Chappell 2001 Foraminifera as Holocene environmental indicators in the South Alligator River, northern Australia. *Quaternary International* 83-85:47–62.

Williams, A. N. 2013 A new population curve for prehistoric Australia. *Proceedings of the Royal Society B* 280:20130486.

Williams, A. N., S. Ulm, I. Goodwin and M. Smith 2010 Hunter-gatherer response to late Holocene climatic variability in northern and central Australia. *Journal of Quaternary Science* 25(6):831–838.

CHAPTER 7

SUMMARY AND CONCLUSION

“Compositions have form and the geographer will see in the landscape a variety of areal patterns and relationships: clusters, nodes, scatterings, gradations, mixtures. These of course take on meaning only when interpreted with some understanding of history and behaviour, and of larger geographic contexts” (Meinging 1979:45)

7.1 State of Archaeological Geophysics in Australia 2012

In 2012, *Australian Archaeology* published the paper entitled ‘Review of Geophysical Applications’ (see Chapter 2) (Lowe 2012). At the time, the goals were to examine the history of archaeological geophysics in Australia and to consider the factors that may have prevented these methods not having been used in many archaeological investigations to date. It concluded by stating that considerations such as costs, time, instrument availability and lack of theoretical knowledge contributed to the limited uptake of these techniques in Australian archaeology. This paper also provided what geophysics could offer today and whether there was potential for Australian archaeologists to develop the skills that were necessary for archaeological prospecting. Several years have passed since its initial publication therefore the following addresses the author’s role in the movement of this discipline in Australian archaeology and whether it has in fact moved forward.

The knowledge that geophysics is a cost-effective way to examine topographical, geological and cultural characteristics of the landscape is well-known and one of the driving forces for the studies that have been undertaken previously in Australia. The standard geophysical methods commonly used in archaeological prospection are electrical resistance, electromagnetic conductivity, magnetometry, GPR and magnetic susceptibility; all work as tools to map, locate and produce images of subsurface cultural material (Clark 1996; Gaffney and Gater 2003; Johnson 2006). Their non-invasive nature and ability to rapidly assess archaeological sites offers great potential in research and in cultural heritage management or when information is not easily available using other means of investigation (Gibbs and Gojak 2009; Moffat et al. 2008; 2010; Wallis et al. 2008).

As stated, a number of factors were listed on why geophysical techniques are rarely used in Australian archaeology. The most important was the perceived cost of the instruments; however, the time required to conduct a geophysical survey and instrument availability were also critical reasons. Other factors, such as the ability for most specialists to understand geophysical anomalies as culturally-generated phenomena were equally valid reasons why these methods have been underutilised. Lastly, the nature of Australia's ancient landscape which includes the sparse nature of the majority of the archaeological record, and on-accumulating landscapes, may have served as a determent for adopting these techniques, particularly in areas that contain complex stratigraphy or depleted landscapes, or where seasonal burning may have existed.

7.2 Has Anything Changed? State of Archaeological Geophysics in Australia in 2014

Since publication of the review, several new projects using geophysical methods have developed throughout Australia, with many of these involving the author. These include a range of techniques which have been applied to a variety of site types (i.e. rockshelters, shell middens and shell mounds, historic sites and cemeteries both Indigenous and non-Indigenous), thus enhancing the understanding of archaeological sites and landscape settings. A number of Australian researchers were interested in geophysics, but as discussed in the review, they did not have many opportunities to use such techniques or collaborate with a person who was skilled in the methodology. The review paper, followed by regional conference presentations and invited guest lectures, and a few training courses within the universities, provided an opportunity to start collaborating with a number of researchers who were interested in these techniques, and soon many projects began to develop. These projects manifested as examples of how these methods could be applied in Australia, encompassing a number of collective research ideas that could be used to address significant questions in archaeology, such as the ones provided in this thesis.

As 2014 began, the list of geophysical-based projects continues to grow and has expanded towards incorporating more remotely sensed applications such as LiDAR and laser scanning (i.e. Australian Archaeological Association conference 2014 Session – Remotely sensed applications in Australian archaeology). The question now is, is this the step towards a greater use of geophysics in Australian archaeology? Looking at the projects that have developed since the review paper was published verifies a change seems to be occurring (Figure 9.1). Although there are some biases since many projects involve this thesis, it is evident that more broadly geophysical applications in archaeology are increasing, particularly as institutions, consultants and local custodians learn about the advantages these techniques offer to archaeological research. Outside this thesis, other publications have emerged that can be added to the list of Australian archaeological geophysics (McKinnon et al. 2013; Sutton and Conyers 2013; Westaway et al. 2013). In addition to the current archaeological geophysics-based doctoral thesis, there are at least several other on-going PhD and honour's theses. All are from different universities (i.e. Griffith University, James Cook University, La Trobe University, The University of Queensland, The University of Western Australia) who are also using these techniques as a part of their research; to the best of my knowledge three years ago there were not any. This further demonstrates that the role of geophysics is changing in Australian archaeology.

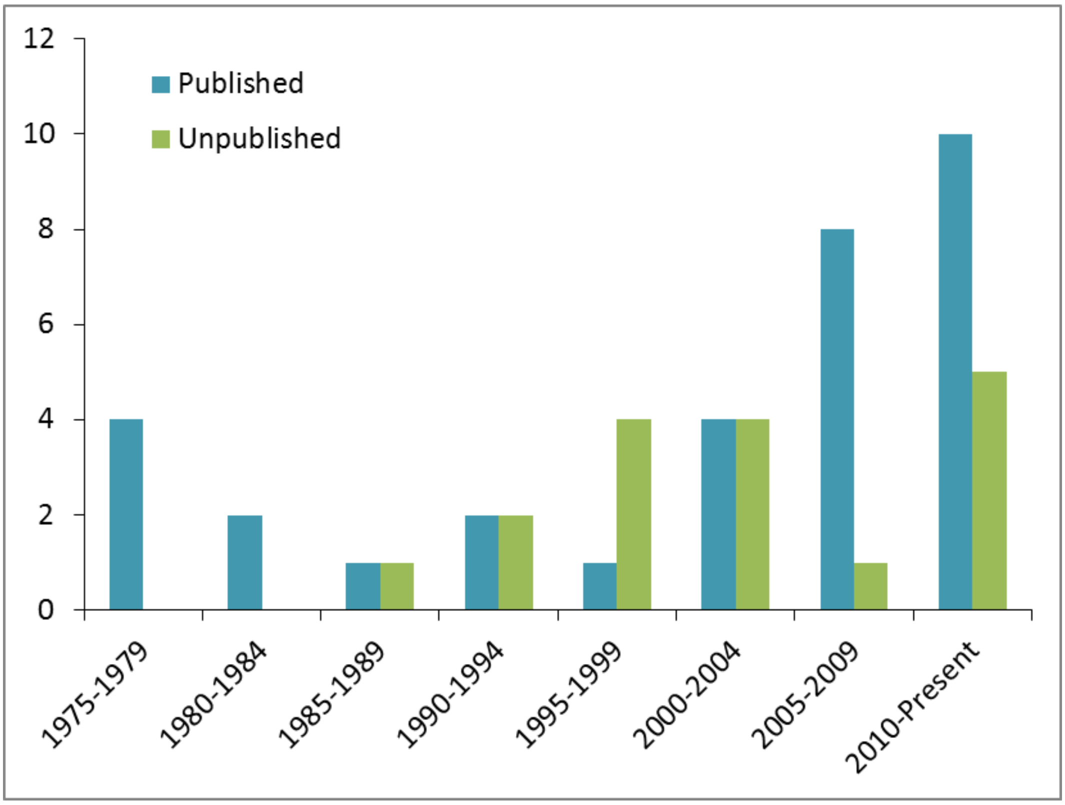

Figure 7.1 **Graph showing the number of published and unpublished papers on geophysical surveys completed in Australia archaeology from 1975 until August 2014. Unpublished material may be lower due to access availability. Note significant increase in use in mid-2000s.**

It is also worth noting that this change in the use of geophysics at other archaeological sites in the world is becoming more global as evidenced by the increase in review papers for other countries (see Viberg 2012). In addition to the review of geophysics in Australian archaeology, reviews have been undertaken in Sweden (Viberg et al. 2011) and Norway (Stamnes and Gustavsen 2014). Such reviews are not only highlighting the value of geophysics in archaeology but also in cultural heritage management, globally. This is an important component for research design and management efficiency.

7.3 Archaeological Geophysics as Landscape –Matter of Scale

The scale of archaeological geophysics also demonstrates its importance when it comes to the material that is mapped and its depositional environment. Mapping at a ‘macro’ scale in archaeology depends on literacy, bibliographical and documentary sources, on toponomy, iconography, epigraphy, historical cartography, aerial photography, satellite imagery and sometimes field survey (Campana and Piro 2009). In contrast, ‘micro’ archaeology is traditionally concerned with the recovery of materials within site and its subsequent analysis and examination (Campana and Piro 2009; Gaffney and Gator 2003). Archaeological geophysics falls into both of these categories, as one can perform a large-scale survey to detect anthropogenic features buried below the surface, such as a buried road or house, or it can perform at finer resolutions, such as to understand sediment inputs causing a geophysical anomaly or a site’s depositional environment.

In this thesis, geophysical investigations included both horizontal and vertical assessments of the study sites, particularly the latter. Magnetic stratigraphic profiling of GS1 and the three Mornington Island middens provided a microgeophysical view of the each site’s formation processes and assisted in the determination of natural and cultural inputs. It also provided a sedimentary record of human occupation by demonstrating that the magnetic assemblage in each stratigraphic profile was largely a result of anthropogenic inputs (i.e. fires). GPR mapping at Madjedbebe provided a macrogeophysical assessment of the site, both vertically and horizontally. Horizontal slice-maps were used to understand the patterning of the geophysical anomalies in the site, which were identified as rocks. Vertical reflection profiles helped estimate the size, depth and strength of wavelengths, since their velocity changed when the wave encountered a buried rock. This then allowed an understanding on how people were buried at the site and a visual interpretation of three-dimensional data set of archaeological features.

When it comes to the matter of scale in archaeological geophysics, the physical nature of the anomalies themselves are what is of interest to the archaeologists. The physical properties of archaeological sites examined for this thesis reflect those changes made to the natural environment by humans. Here the magnetic minerals, combined with the artefactual material, were the physical properties that allowed confidence in understanding when humans arrived at an interior corridor site, confirmation that occupation was continuous in a Pleistocene rockshelter and that people repeatedly occupied shell midden sites in the late Holocene despite their seemingly instantaneous deposition based on radiocarbon dating. The physical property of rocks allowed for an understanding of the cultural inputs within a rockshelters drip-line – the act of placing rocks deliberately over a burial as part of a burial practice.

7.4 Conclusions and Future Prospects

The aim of this thesis was to develop geophysical methods that could be used to address fundamental questions in Australian archaeology. Presently, the archaeological application of geophysical techniques has become widespread throughout the world; however, their use in Australia has been limited. Despite this, there has been great potential to use these methods to inform archaeologist about sites that may not always be achieved using traditional methods alone and this thesis provides multiple examples of how this can be achieved. Further, to move away from projects which use these applications as a way to find archaeological features prior to excavation, this thesis adopted a shift towards using these tools to study the human past.

A key component to this study was to understand humans and their environment. The research areas included two Pleistocene-aged sandstone rockshelters and three Holocene-aged shell mounds in northern Australia. Specifically, sediment magnetic susceptibility studies were integrated with geoarchaeology and geochronology, to understand the record of occupation, depositional history and paleoenvironment at all of these sites. GPR, combined with archaeological excavation and GIS mapping, was used to understand complex burials.

Chapters 3–6 demonstrate how geophysical techniques were used to address important questions in Australian archaeological research. While Chapter 2 examined the history and use of geophysical techniques, the remaining chapters reflected critical themes in the field of Australian archaeology, including how: 1) magnetic changes in a sedimentary deposit can be used to determine the onset of human occupation; 2) magnetic changes can be used to understand the nature and persistence of human occupation in a rockshelter site; 3) GPR can be used to identify complex burials and support traditional understandings of burial practices; and 4) magnetic changes can reveal repeated occupation events.

At GS1, magnetic changes in the sedimentary deposit were determined to be the result of cultural activity. An experimental burning program using off-site samples was conducted to confirm that magnetically enhanced sediments in the cultural deposits were the result of anthropogenic burning rather than natural fires, pedogenesis or weathering. The change in magnetics coincided with the level at which stone artefacts appear on the site, indicating that artefactual material is *in situ* and has not moved down through the sequence from higher layers above. The ability to link the first appearance of stone artefacts with an increase in magnetic susceptibility is a critical development in Australian archaeology as it provides an opportunity to re-examine early archaeological sites where associations between dated sediments and stone artefacts are disputed, such as the Madjedbebe site. Further, it can also provide targets for luminescence dating, since the earliest archaeological sites are based on luminescence dating of sediments, rather than directly of cultural materials. It can also be used to resolve issues about the continuity of occupation of sites, especially when the association between sediments and the evidence of human activity is questionable.

Sediment magnetic susceptibility was also combined with micromorphology and other sedimentary and archaeological data at GS1 to show that the site was used by people around 38,000 years ago in a region that has been characterised as a potential corridor for early colonists moving southward across Australia and the arid interior. The data also revealed that occupation was continuous through the LGM without any abandonment of the site. This has important implications for our understanding of climatic conditions during that period, as it allows us to infer that water must have been available regionally in order for people to have maintained their use of the site; we tentatively suggested this may have resulted from the monsoons driven by the Coral Sea off the northeast Australian coastline still being active during this time. These findings suggest that the region was perhaps more favourable, for human occupation than that at present. This study demonstrated how an integrated geoarchaeological approach can contribute to debates about how people spread across Australia and responded to climatic changes through the late Quaternary. The results were also effective for understanding anthropogenic inputs and the complicated stratigraphy at the site.

At Madjedbebe, GPR was able to identify a number of subsurface rocks within the sandstone rockshelter’s drip-line that were associated with human burials. Post-excavation, GIS and statistical analysis was used to further elucidate this relationship between the rocks and human burials. Graves were dug into shell midden deposit and rocks were placed on the individuals before being covered. These rocks were the source of large reflections in the GPR data, and detailed archaeological mapping and excavation verified their location. Insights into burial practices derived from ethnographic sources further supported the geophysical interpretation and provided an opportunity to test a way to identify unmarked burials. Application of this methodology not only documents a marker for burial identification in this region, but also provides a useful management tool for Indigenous communities and heritage practitioners.

In coastal areas, shell matrix sites are commonly used to establish regional chronologies of human occupation, especially around the northern Australian coastline. Here, a range of sedimentary and archaeological analyses, combined with magnetic susceptibility, demonstrated that people repeatedly visited three anthropogenic mounds on an island in the Gulf of Carpentaria. Despite archaeological evidence including radiocarbon dates suggesting instantaneous deposition at each shell mound, the integration of geoarchaeology and magnetic susceptibility revealed information about each site's formation process and confirm that people used the mounds on more than one occasion. This study has important implication for other shell mound sites, especially where the limitations of radiocarbon dating may mask multiple depositional events.

7.4.1 Future Research

The mineral magnetic analysis conducted at GS1 has clearly demonstrated there is great potential to use this technique to re-examine early archaeological sites in northern Australia where the associations between dated sediments and stone artefacts are disputed, such as Madjedbebe. Madjedbebe, one of Australia's oldest rockshelters, has been heavily involved in initial colonisation debates because artefacts found several meters below the surface yielded dates between 50,000 to 60,000 years old (Roberts, et al. 1990). Many archaeologists are doubtful of these age determinations and question the stratigraphic associations at the site (Allen 1994; Allen and O'Connell 2003; Bowdler 1990, 1991; O'Connell and Allen 1998; O'Connell and Allen 2004; Roberts et al. 1990). A key concern for many is that the ages proposed for the earliest archaeological sites are based on luminescence dating of sediments and not cultural material as stated in the preceding paragraphs. Many argue that vertical movement of artefacts, especially those found in the deepest layer are not associated with those lower deposits and consequently, the dates estimated for the site are inaccurate. Since magnetic changes coincide with the level of onset of human occupation in GS1, the next step would be to examine the mineral magnetics at other Pleistocene-aged sites to determine whether there is a similar correspondence between the first appearance of artefacts and an increase in magnetic susceptibility indicating intense burning in the site. This could then resolve the issue of whether artefacts have translocated down the sequence.

The mineral magnetic analysis and integration of geoarchaeology also provided evidence of human occupation during the LGM at GS1. While no obvious source of permanent water is near the site, the study revealed that people did not abandon the site or the region as seen at other Pleistocene sites. Another challenge for researchers would be to locate other sites of similar antiquity in the region to test whether an LGM occupation exits in this interior corridor. This would build on resolving those issues mentioned above and provide a better chronology of Pleistocene occupation in this region. Additionally, the integration of magnetic susceptibility with micromorphology in particular demonstrated their value in understanding the sedimentological record. Both are good indicators of horizonation yet this was absent in the GS1 sequence. Discrete boundaries were also not identified. Post-depositional mixing by humans and insects further resulted in abrasion and lateral reworking of deposits. However, the appearance of stone artefacts, ground ochre and wood charcoal throughout the GS1 sequence indicate that no cultural or temporal hiatus such as is apparent in many other Pleistocene sites in Sahul (cf. David et al., 1997; O’Connor et al., 2003). If sites are abandoned, one would expect to see this ‘hiatus’ in the stratigraphic record. Therefore, determining other patterns using magnetic susceptibility and micromorphology could provide more detailed information on a sites formation processes such as pedogenesis, weathering or if a lag or hiatuses occurs.

Studies such as that undertaken at Madjedbebe have the potential to provide information on the intra- (individual burial and cemetery practices) and inter-site (regional variation and territorial organisation), especially where information about the cultural history may be lacking. The next step would be to test whether this type of burial practice occurs at other rockshelter sites in the region. GPR surveys are extremely rare in Australian rockshelter studies, yet rockshelters appear to be the dominant site type investigated. If researchers started utilising this method in complex archaeological sites, perhaps they could alert researchers and managers to the possibility of burials being present, thereby allowing communities to be more informed prior to considering permission to excavate or in other cases, choose avoidance.

Finally, the integration of geoarchaeology and magnetic susceptibility help establish subtle changes in three shell mounds. In Australia, understanding the formation history of shell matrix sites can be quite complicated. While in large shell mounds, stratigraphic layering is generally more obvious than on many smaller mound sites, which have no evidence of layering and instead appear as a single homogenous deposit (Faulkner 2013; Morrison 2013; Rosendahl et al. 2014; Shiner et al. 2013) A challenge would be to test whether stratigrahic changes are observed in other shell matrix sites, especially those have been documented as being ‘archaeologically instantaneous’ in terms of their period of deposition, without any visible stratigraphic evidence to suggest otherwise. Further research examining the magnetic variations associated with the anthropogenic inputs and sediment changes using other magnetic parameters would also enhance the results, since the initial pilot study only looked at the magnetic susceptibility and not the mineral magnetics.

References

Allen, J. 1994 Radiocarbon determinations, luminescence dating and Australian archaeology. *Antiquity* 68:339–343.

Allen, J. and J. F. O'Connell 2003 The long and the short of it: Archaeological approaches to determining when humans first colonised Australia and New Guinea. *Australian Archaeology* (57):5–19.

Bowdler, S. 1990 50,000 year-old site in Australia - Is it really that old? *Australian Archaeology* 31:93.

Bowdler, S. 1991 Some sorts of dates from Malakunanja II: A reply to Roberts et al. *Australian Archaeology* 32:50–51.

Campana, S. and S. Piro (eds) 2009 *Seeing the Unseen: Geophysics and Landscape Archaeology*. London: Taylor and Francis Group.

Clark, A. 1996 *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Routledge.

David, B., R. G. Roberts, J. Magee, J. Mialanes, C. Turney, M. Bird, C. White, K. L. Fifield and J. Tibby 2007 Sediment mixing at Nonda Rock: Investigations of stratigraphic integrity at an early archaeological site in northern Australia and implications for the human colonisation of the continent. *Journal of Quaternary Science* 22(5):449–479.

Faulkner, P. 2013 *Life on the Margins: An Archaeological Investigation of Late Holocene Economic Variability, Blue Mud Bay, Northern Australia*. Terra Australis 38. Canberra: ANU E Press.

Gaffney, C. and J. Gater 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing Ltd.

Gibbs, M. and D. Gojak 2009 Remote sensing in an urban Australian setting. *Australian Archaeology* 68:45–51.

Johnson, J. K. (ed.) 2006 *Remote Sensing in Archaeology: An Explicitly North American Perspective.* Tuscaloosa: University of Alabama.

Lowe, K. M. 2012. Review of geophysical applications in Australian archaeology. *Australian Archaeology* 74:71–84.

McKinnon, J. D. Wesley, J. Raupp and I. Moffat 2013 Geophysical investigations at the Anuru Bay trepang site: A new approach to locating Macassan archaeological sites in Northern Australia. *Australasian Institute for Maritime Archaeology* 37:107–113.

Moffat, I., L. A. Wallis, A. Beale and D. Kynuna 2008 Trialing geophysical techniques in the identification of open Indigenous sites in Australia: A case study from inland northwest Queensland. *Australian Archaeology* (66):60–63.

Morrison, M. 2013 From scatter to mound: A new developmental model for shell mound sites at Weipa. *Queensland Archaeological Research* 16:165–184.

O'Connell, J. F. and J. Allen 1998 When did humans first arrive in greater Australia and why is it important to know? *Evolutionary Anthropology* 6:132–146.

O'Connor, S., P. Veth and A. Barham 1999 Cultural versus natural explanations for lacunae in Aboriginal occupation deposits in northern Australia. *Quaternary International* 59:61–70.

Rosendahl, D., K. M. Lowe, L. A. Wallis and S. Ulm 2014 Integrating geoarchaeology and magnetic susceptibility at three shell mounds: A pilot study from the Gulf of Carpentaria, Australia. *Journal of Archaeological Science* 49:21–32.

Shiner, J. S., P. C. Fanning, S. J. Holdaway, F. Petchey, C. Beresford, E. Hoffman and B. Larsen 2013 Shell mounds as the basis for understanding human-environment interaction in far north Queensland, Australia. *Queensland Archaeological Research* 16:65–91.

Stamnes, A. A. and L. Gustavsen 2014 Archaeolgical use of geophysical methods in Norwegian cultural heritage management – A review. In H. Kamermans, M. Gojda and A. G. Posluschny (eds), *A Sense of the Past: Studies in Current Archaeological Applications of Remote Sensing and Non-Invasive Prospection Methods*, pp. 17–31. BAR International Series 2588. Oxford: Archaeopress:

Sutton, M.-J. and L. B. Conyers 2013 Understanding cultural history using ground-penetrating radar mapping of unmarked graves in the Mapoon Mission Cemetery, Western Cape York, Queensland, Australia. *International Journal of Historical Archaeology* 17(4):782–805.

Viberg, A. 2012 *Remnant echoes of the past: Archaeological geophysical prospection in Sweden*. Theses and papers in Scientific Archaeology 13. Department of Archaeology and Classical Studies. Stockholm: Stockholm University.

Viberg, A., I. Trinks and K. Lidén 2011 A review of the use of geophysical archaeological prospection in Sweden. *Archaeological Prospection* 18(1):43–56.

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

Westaway, M. C; M. L. Cupper, H. Johnston and I. Graham 2013 The Willandra fossil trackway: Assessment of ground penetrating radar survey results and additional OSL dating at a unique Australian site. *Australian Archaeology* 76: 84–89.

APPPENDIX A

METHODS OF INVESTIGATION

1.1 Introduction

Archaeological geophysics works as a prospection tool to map, locate and produce images of subsurface cultural material at archaeological sites using five standard methods: electrical resistance, electromagnetic conductivity, magnetometry, magnetic susceptibility and ground penetrating radar (GPR). Each of these methods is capable of mapping buried remains through the detection of physical and chemical changes in subsurface properties. Geophysical maps, typically showing horizontal variations although vertical variations (similar to stratigraphic sections) can also be represented, are created by the act of systematic data collection, as geophysical instruments are either dragged across the ground surface using tightly spaced survey transects or sampled vertically through either field or lab based devices. Maps then produced reveal geometric patterns or trends in the data that can be used to assist in the understanding of archaeological deposits.

Site sediments themselves can also be examined through the use of geophysical methods particularly those involving mineral magnetic studies. These analyses can assist in the stratigraphic interpretation of sites, because they allow an examination of those physical properties created by anthropogenic modifications. Detailed sediment analysis using geoarchaeological techniques such as micromorphology enables an assessment of the geophysical observations and can help distinguish anthropogenic inputs from those that are natural. These methods also provide information on post-depositional processes. When combined with standard excavation methods, they provide a complementary way to understand archaeological sites.

As part of this thesis research, the ultimate goal was to develop new methods that could be used to address important questions in Australian archaeology. Here, magnetic susceptibility and mineral magnetics were used with other techniques such as geoarchaeology, soil chemistry and geochronology to understand the record of occupation, stratigraphy and site formation processes on Gledswood Shelter 1 (GS1) and on the three shell mounds on Mornington Island. Specifically, these techniques were used to understand human occupational patterns in northern Australia by addressing three research questions: 1) can magnetic susceptibility be used to understand archaeological site formation processes, including determining the onset of human occupation, and resolving issues regarding artefact movement and apparently ‘instantaneous’ deposition of materials; 2) can magnetic susceptibility be used to understand the nature and persistence of human occupation at a Pleistocene-aged rockshelter in interior Australia, with particular emphasis on the relationship with changing climatic regimes such as the LGM; and 3) can magnetic susceptibility when integrated with geoarchaeology, be used to understand whether open sites (shell mounds) on Mornington Island, Gulf of Carpentaria, were repeatedly visited? Additionally, GPR was used for this thesis project to understand burial practices and site formation processes at a rockshelter site, and addressed the fourth question 4) can GPR be used to identify human burials at the Madjedbebe site, located in western Arnhem Land, and if so, can it also be used to support pre-existing traditional knowledge of burial practices?

A list of publications and books describing comprehensive theoretical applications of archaeological prospection (Bevan 1998; Clark 1996; Conyers and Goodman 1997; Gaffney and Gater 2003; Johnson 2006; Scollar et al. 1990; Witten 2006), and environmental magnetism (Evans and Heller 2003; Thompson and Oldfield 1986) have already been provided. Therefore, for this thesis the following section describes only a brief summary of the methods used for this research emphasising basic concepts and theory. For more information please refer to those authors listed above. The primary geophysical methods used for this thesis include soil magnetic susceptibility, mineral magnetics and GPR. For details on their methodological application specific to each research question refer to Chapters 3 and 4 for magnetic susceptibility and mineral magnetics, Chapter 5 for GPR, and Chapter 6 for only magnetic susceptibility. A brief summary on both geoarchaeological and geochronological applications is also provided in this chapter. For methodological details on those used for this research please refer to Chapters 3, 4 and 6.

1.2 Magnetic Susceptibility

Magnetic susceptibility has been defined numerous times throughout this thesis therefore the purpose of this section is to provide a brief over view of basic concepts and theory. Within the last several decades, it has become a popular technique in archaeological prospection because it has the ability to 1) define sites, activity areas, features, buried soils and cultural layers, 2) build and correlate stratigraphic sequences, and 3) understand site-formation and post-depositional processes (Dalan 2001:263). Interestingly, some of the most subtle effects in magnetic surveys are a result of magnetic susceptibility because variations in susceptibility between certain soils affect the earth’s field locally, making it possible to detect buried cultural features and layers.

Archaeologically, the use of magnetic susceptibility goes back as early as 1965 with Le Borgne's pioneering work on susceptibility enhancement (see following section). This was soon followed by other studies, mainly in England on Iron-Age sites (see Tite and Mullins 1971: Tite 1972a). Most recently, Dalan (2008) has synthesised the roles and prospects of this method in North America, where investigations included both horizontal and vertical geophysical assessments. Such studies include those within trenches and excavation units, magnetic stratigraphic profiling and visual interpretation of three-dimensional data sets of archaeological features. These recent prospects also demonstrate the scale of this application, thus allowing one to examine from a microgeophysical view, from that of a single excavation unit to one that looks at the broad cultural landscape (Dalan 2008).

1.2.1 Mechanisms for Soil Enhancement

Research on magnetic susceptibility studies first began in the 1950-60s with work conducted by Le Borgne, who identified fire as a primary mechanism for magnetic enhancement in soils. Fires, either human-induced or naturally occurring, thermally alters weakly magnetic iron oxides to more magnetic oxide forms and produces high temperature and anaerobic conditions that are favorable to magnetic enhancement (Le Borgne 1955, 1960, 1965). When exposed to this set of circumstances, hematite in the soil changes over to magnetite and maghemite and as a result, magnetic susceptibility is created (Dunlop and Özdemir 1997:377–381).

Le Borgne (1965) continued researching the mechanisms that caused magnetic enhancement in soils, and identified a second factor he defined as the 'fermentation mechanism,' which was proposed later by Mullins (1977). Fermentation, which is a process that usually occurs in the upper soil layers, is the interaction of soil organic matter and soil iron during pedogenesis (Dalan and Banerjee 1998), and has been described as the oxidation/reduction cycles of periodic wetting and drying in these upper soil layers (Le Borgne 1965). The partial dehydration and reduction of ferrihydrite, an easily reduced iron oxide, to magnetite in the presence of excess ferrous iron is what gives a rise to soil magnetic enhancement (Dearing et al. 1996:94; Evans and Heller 2003). This second ferromagnetic mineral formation occurs in temperate soils. Work conducted by Dalan and Banerjee (1998:4) have shown that Le Borgne's 'fermentation mechanism' are as important as fire-induced enhancement when studying magnetic enhancement especially because of its success in palaeoclimate reconstructions (Ding et al. 1999; Maher and Houslow 1999; Mooney 1997). Microbiota, small organisms found in the upper soil layers are another form of enhancement. Their activity influences the precipitation of ferric iron oxides in soils causing ferrous iron oxidation

(Fassbinder et al. 1990; LeBorgne 1955; Maher 1986). They do this by releasing organics into the soil, or by utilising iron for their metabolism.

Mullins and Tite (see Longworth and Tite 1977; Mullins 1977; Mullins and Tite 1973; Tite 1972a, 1972b; Tite and Mullins 1971) continued to pioneer Le Borgne's work in understanding the process of enhancement, its effects on soils from archaeological sites and the implications for the successful use of magnetic prospecting techniques on archaeological deposits. They compared non-cultural 'natural' soils subjected to fire to those that have been anthropogenically altered by firing (Dalan and Banerjee 1998:4). While their results confirmed that fire was a primary cause of soil magnetic enhancement, Mullins and Tite (1973) also attempted to explain why intra-site variation in susceptibility values occurred. The geological strata responsible for the parent material of the soil, the quantity of organic matter present in the topsoil and the duration and intensity of the fire all played a role in determining susceptibility values and that 'fermentation' proposed by Le Borgne had minimal effects when compared to fire enhancement (Tite and Mullins 1971).

It has now been demonstrated that the amount of organic matter, iron content and porosity of the soil as well as the temperature reached, play a major role in magnetic enhancement created through fires (Dalan and Banerjee 1998; Fitzpatrick 1985; Maher 1986; Oldfield et al. 1981). However, recent work (Evans and Heller 2003:92–95) states there are now five known causes of soil enhancement: 1) fire, both anthropogenic and naturally occurring, 2) the 'fermentation mechanism,' 3) bacterial microorganisms, 4) inorganic *in situ* formation of ultra-fine grained magnetite, and 5) detrital input from modern pollutants.

Laboratory tests demonstrated a fourth cause of soil magnetic enhancement, is the *in situ* formation of ultra-fine grained magnetite. This formation could be synthesised through controlled oxidation of ferrous iron solutions at room temperatures and near neutral pH (Maher and Taylor 1988; Taylor et al. 1987) since synthetic material was similar in chemical composition, morphology and grain size to soil analogues containing ultra-fine grained magnetite. The final cause of soil magnetic enhancement is the detrital inputs (i.e. fallout in the atmosphere) of fossil fuel–burning from power plants, metallurgical industries and cement factories (Evans and Heller 2003:92). Detrital inputs are coarse-grained balls of magnetite generated by a number of sources that are transported as dust particles before they eventually land on the soil surface and penetrate into the upper soil layers.

The two rockshelters in this study, GS1 and Madjedbebe, are comprised of weakly magnetic quartzose sandstone. The three open sites on Mornington Island: Guttapercha, Mala Katha and Munburlda; are comprised primarily of weakly magnetic quartz sand. Based on these geological properties, factors for magnetic enhancement at these sites should result primarily from burning (human induced or natural) or by pedogenesis (i.e. fermentation and microbiota). However, chemical weatherings such as the dissolution or cation substitution of magnetic minerals (cf. Evans and Heller 2003) or the formation of bacterial magnetosomes (cf. Linford 2005) are also potential mechanisms for magnetic enhancement.

1.2.2 Measuring Magnetic Susceptibility

All atoms react to magnetic fields and because these fields are generated by their orbiting electrons, they have a magnetic susceptibility which is denoted by the Greek letter Kappa (K) (Clark 1996). When K is slightly negative, this is known as diamagnetism. Materials with positive susceptibility (especially strong in iron) become magnetised by a small alternating magnetic field (i.e. 0.5 to 1.0 Oersted [Oe]) and this induced, not permanent magnetisation, is defined by the ratio of the intensity of the induced field to that of the magnetic field, or $K=M/H$ (Banerjee 1981). Because M and H are both measured in ampere per meter (A/m), the ratio is a dimensionless quantity therefore, susceptibility is generally expressed in two ways.

The first way is volume susceptibility (K) or (SI), in which susceptibility is normalised to the measured sample's volume. K is defined by the relation $K=M/H$, where M is the magnetisation per unit volume acquired from H and H is the uniform magnetic field applied (Figure 1). The second way susceptibility is expressed is low field mass susceptibility which is represented by the Greek letter Chi (χ).

Here susceptibility is normalised by the mass of the sample and χ is defined by the volume susceptibility divided by the density, $\chi= K/\rho$ (see Figure 1). With mass, the readings are no longer dimensionless and χ has units expressed as (m^3/kg). Generally magnetic susceptibility is measured in smaller field of less than 1 millaTesla (mT). This low field approach allows susceptibility to be measured reasonably independent of the applied field intensity (Thompson and Oldfield 1986).

1.2.3 Instrumentation

A number of instruments can be used to collect magnetic susceptibility data. The most commonly used ones are those used in the field because they can cover large areal surveys. Some of the more popular field instruments in archaeology include the Geonics EM38-M2K and Geophysical Survey Systems Inc., (GSSI) EM Profiler (Figures 2). These instruments work by inducing a primary electromagnetic field into the soil. A coil is located at the front of the instrument and is responsible for the transmission of the first magnetic field. This produces a second magnetic field by the eddy currents, which is then received by the coil located at the other end of the instrument (Figure 3) (Reynolds 1997). The operator has the option of choosing to measure the in-phase (IP) or magnetic susceptibility, or quadrature (Q) phase or conductivity of the electromagnetic wave. The in-phase component is a measurement of the magnetic component of the electromagnetic wave, while the quadrature is a measure of the electric component (West and Macnae 1991).

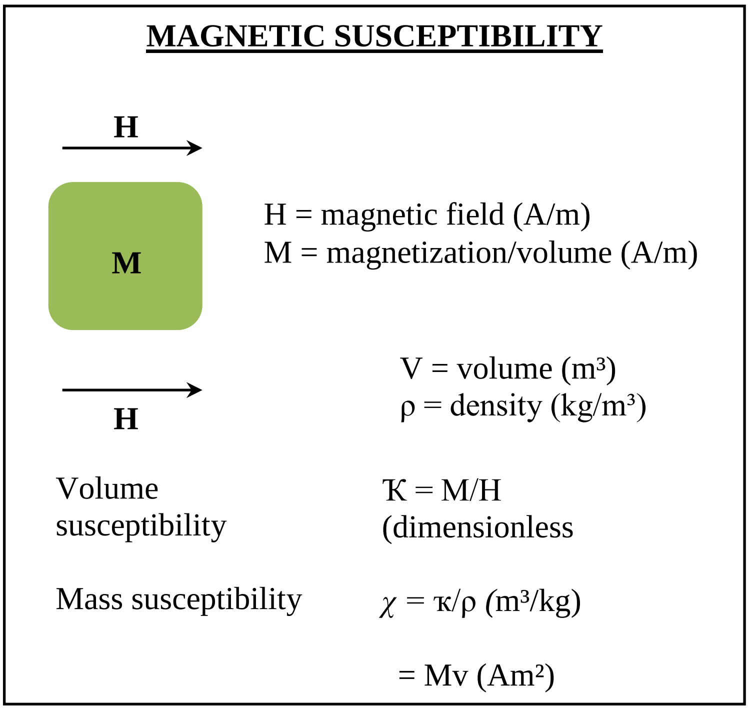

Figure 1. **Diagram showing how magnetic susceptibility can be expressed (Evans and Heller 2003: Figure 2.1).**

Figure 2. **Geonics EM38B dual electromagnetic conductivity and magnetic susceptibility meter with data logger. Transmitter is located in the front of the instrument, receiver in back, spacing between is 1 m.**

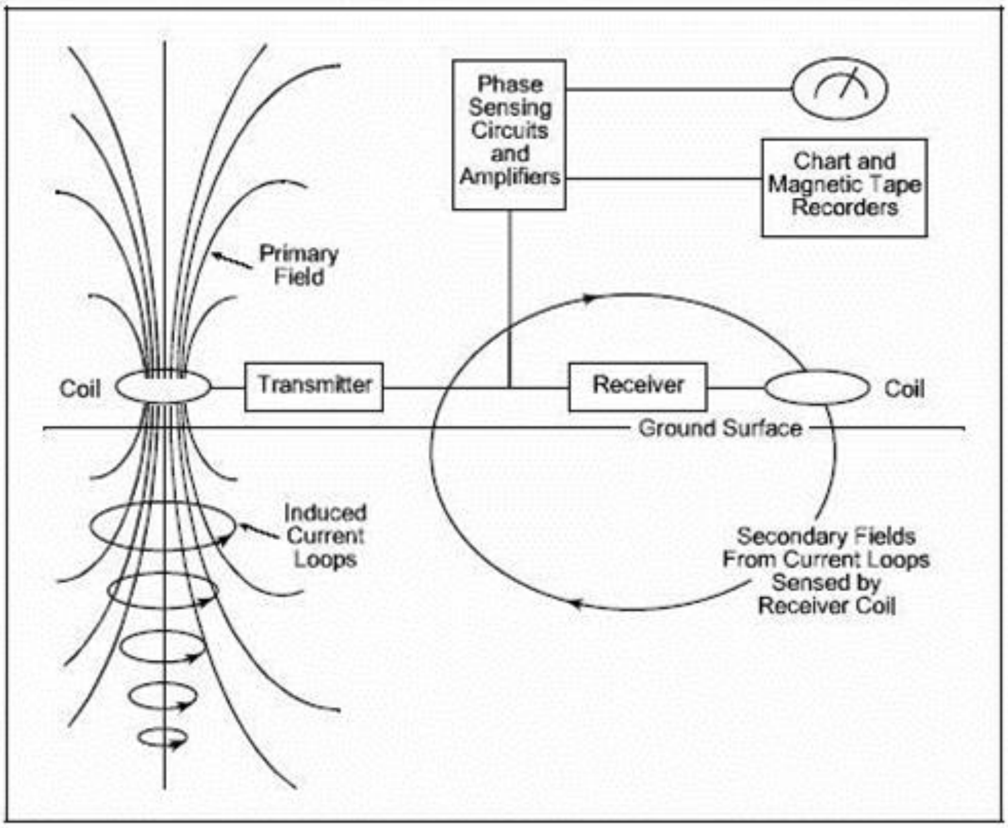

Figure 3. **Generalized diagram of electromagnetic induction principles. Induced current flow from the transmitter coil to the receiver coil (United States EPA 1993).**

Another instrument, less commonly used but also capable of surveying large areas is the Bartington Instruments Ltd MS3 Magnetic Susceptibility Meter with a MS2D Field Search Loop (Figure 4). This two-field coil instrument, with penetration depths of ca 10 to 1 cm, has been successful in mapping site activity areas in topsoil surveys or living floor spaces within large excavation units (Dalan 2008; Rosendahl et al. 2013).

Figure 4. Bartington Instruments MS3 magnetic susceptibility meter with a MS2D field search loop (pictured left) (courtesy of Dan Rosendahl).

In addition to large areal surveys, there are also instruments that measure magnetic susceptibility in finer increments in both bore-hole and lab based applications. The Advance Geoscience Instruments Company (AGICO) Inc. and the aforementioned Bartington Instruments are just two types that measure susceptibility in finer units. The AGICO Inc. uses bridge circuits as one type of alternating current to measure susceptibility while the Bartington Instruments system uses the portable MS2 and MS3 meters and associated suite of induction sensors, each of which is specifically designed for a particular application (Dearing 1999:8) (Figures 5). The later of the susceptibility meters was used for this thesis project. Details on the sample methodology and magnetic parameters are provided in Chapters 3, 4 and 6.

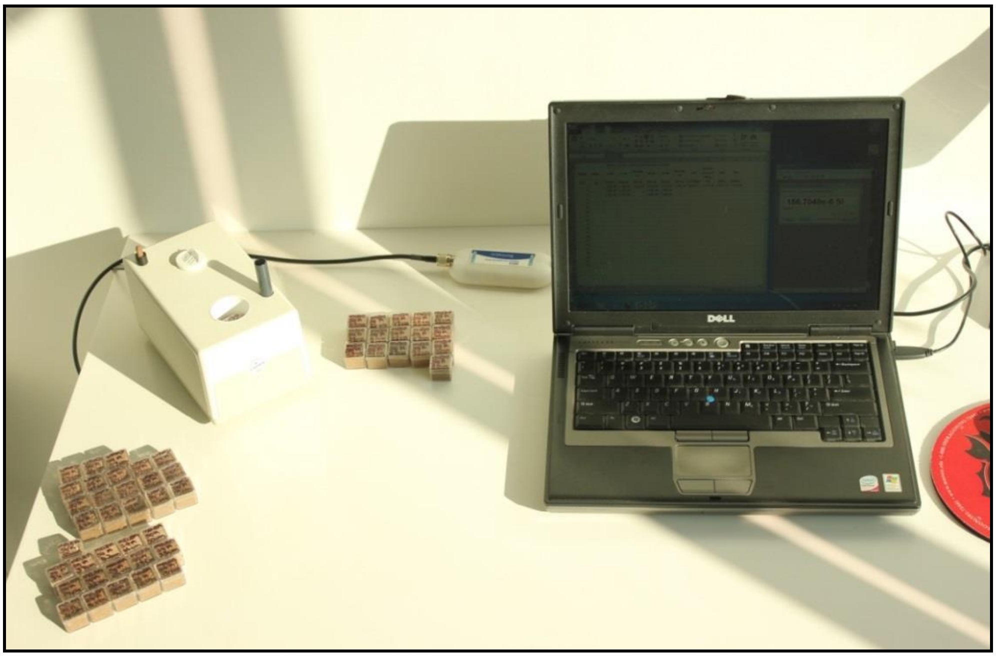

Figure 5. **Bartington Instruments MS3 (top center) with MS2B lab sensor (left) and laptop computer (right). Note sediment samples packed in non-magnetic Althor P-15 boxes.**

1.3 Environmental Magnetism – Archaeomagnetics

The study and utilisation of the magnetic susceptibility of soils and sediments are part of the developing subject of environmental magnetism and may be the most widely applicable proxy in cultural landscape studies (Thompson and Oldfield 1986). Applications of soil magnetic studies to investigate natural and cultural environments has become popular for several reasons, firstly, because iron is one of the Earth's crust most common elements and secondly, that all substances exhibit some form of magnetic behavior (Evans and Heller 2003:1). Mineral magnetic studies provide one way to understand environmental conditions, and knowledge about relevant magnetic properties is important as magnetic investigations can reveal differing physical aspects of sediment properties and mineralogy.

The application of mineral magnetics to archaeology has only begun to emerge in the last few decades and presently many studies continue to use these techniques to supplement both geophysical and geoarchaeological interpretations. Many studies have focused on understanding complex stratigraphic sequences and cultural landscapes (Dalan and Banerjee 1998; Dalan 2006). Other researchers have focused on burnt sediments (Bellomo 1993; Herries and Fisher 2010; Linford and Platzman 2004; Oldfield and Crowther 2007), burnt clay (Jordanova et al. 2001) and hearths (Maki 2005; Marmet et al. 1999). More recently mineral magnetics is being used to source archaeological materials such as weakly susceptible cherts, silicified wood or obsidian (Frahm and

Feinberg 2013; Thacker and Ellwood 2002) and pigments in rock art (Milani 2010; Mooney et al. 2003). It is also being used as a way to test geophysical anomalies (Lowe and Fogel 2010), specifically anomalies associated with burials (Dalan et al. 2010; Moffat et al. 2010) and to understand palaeoenvironmental data (e.g. Ellwood et al. 1997; 2004; Herries 2006; Herries and Latham 2009; Linford et al. 2005).

Magnetic susceptibility studies on rockshelter or cave deposits although minimal, have also shown to be successful for understanding stratigraphy. Largely these studies have been focused in Europe and South Africa (e.g. Ellwood et al. 2004; Herries and Fisher 2010; Herries and Latham 2009), with only a few case studies in Australia (e.g. Keys 2009; Marwick 2005). However, those studies elsewhere have shown the importance of this method in understanding archaeological deposits, especially as they relate to human occupation, formation processes and palaeoclimate interpretations (cf. Ellwood et al. 1995; 1997; Herries 2006; Linford et al. 2005).

1.3.1 Magnetic Mineralogy

In order to understand magnetic mineralogy, one must first understand basic principles in magnetism. Atoms within any substance have electronic structures in which electrons circulate in an orbit around a nucleus. This circulation generates an electrical current, since electrons contain electrical charges, and as a result produces a magnetic moment (Mullins 1977:224) (Figure 6). Consequently, all electrons contain magnetic moments (i.e. quantity that determines the magnetic force exerted) because of their spins. However, many elements contain zero magnetic moments (the torque of an external magnetic field) since the orbital and spin components cancel one another out. Magnetism occurs when the property of these atoms is placed in a magnetic field, causing the rearrangement of the spin and orbital motions. This configuration, interaction and movement of electrons in an atom define the overall magnetic behavior of a rock mineral (Dearing 1999:6).

Three basic properties of magnetism are: diamagnetism, paramagnetism and ferromagnetism. Diamagnetism is a property of all materials. When a magnetic field is applied to a diamagnetic object, a magnetic field in opposition of the applied one is created (i.e. it is repulsive when placed in a field). When this field is removed, the object is then reduced to zero. Specifically, the motion of electrons orbiting the nucleus is altered by the applied field, which changes the magnetic dipole movement (Evans and Heller 2003:7). Many minerals that occur naturally in sediments, rocks and soils such as quartz (SiO_2) or feldspar, are diamagnetic and these generally have negative magnetic susceptibilities. Unlike diamagnetism, objects that are paramagnetic are attracted to applied magnetic fields. Since their electrons possess both spin and orbital magnetic moments, the atom has a permanent magnetic moment and a positive magnetic susceptibility (Evans and Heller 2003; Thompson and Oldfield 1986). However, similar to diamagnetism, when the field is removed, the objects are reduced back to zero. Magnesium, fayalite (Fe_2SiO_4) or lithium are a few examples of paramagnetic materials. The most common as well as strongest property of magnetism is ferromagnetism. With ferromagnetic materials, the atoms are located very close to one another causing the electron orbit to overlap, which then producing a strong interaction (Thompson and Oldfield 1986). This causes the magnetic moments to align (i.e. parallel arrangement), which then gives rise to a strong magnetisation (Evans and Heller 2003:9) (Figure 7). It is associated mainly with the elements of iron, nickel and cobalt but also occurs in iron oxides and natural minerals.

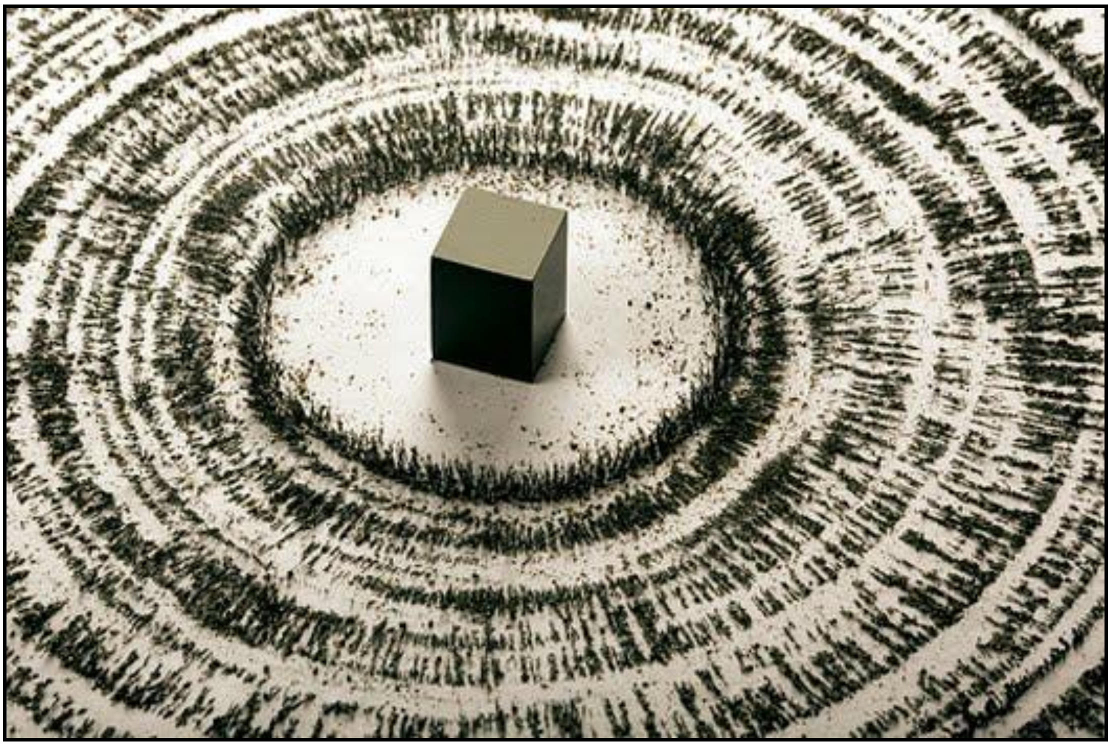

Figure 6. Reaction of iron filings when placed next to magnet with a strong magnetic moment. The circular pattern results from the magnetic field produced by the magnet (http://www.triangulationblog.com/2010/08/magnetism.html).

Soils rich in iron minerals commonly found at archaeological sites are ferrimagnetic (meaning that their magnetic moments are antiparallel of different magnitudes) and antiferromagnetic (meaning their magnetic moments are antiparallel but strengths are identical) (see Figure 7). Minerals that are ferrimagnetic are magnetite (Fe_3O_4) and maghemite (Fe_2O_3); minerals such as hematite (αFe_2O_3) and goethite (α-FeOOH) are antiferromagnetic. All, with the exception of goethite, are iron oxides (the fourth most abundant element of Earth); goethite is an iron oxyhydroxide meaning they are oxidised hydroxides of iron.

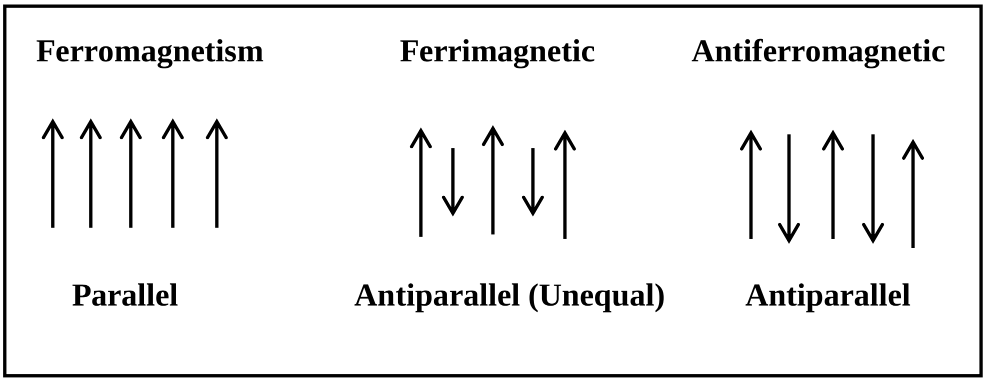

Figure 7. Arrangement of magnetic moments.

Magnetite is the single most important mineral on earth (Dunlop and Ozdemir 1997) and occurs in igneous, sedimentary and metamorphic rocks. It is also a common secondary mineral derived through chemical and bacterial processes or produced during burning (Thompson and Oldfield 1986). Maghemite also occurs widely in soils and is the fully oxidised form of magnetite. Studies have shown that magnetite converts to maghemite during the cooling down of fires in an oxidizing atmosphere (Mullins 1977; Tite and Mullins 1971). Hematite also occurs widely in soils and sediments and is an important mineral in oxidised igneous rocks. When heated, it converts to a strong magnetite. It can also reduce during fermentation with the decay of organic matter in anaerobic conditions. Goethite is less common on archaeological sites but a very common mineral, typically formed as a weathering product in soils of humid climates (Thompson and Oldfield 1986).

1.3.2 Measuring Magnetic Minerals

Magnetic minerals with different mineral properties provide a natural archive of the environmental processes that are found in archaeological sites and sediment studies. Mineral magnetic parameters can be measured separately or in combinations using magnetic fields, temperatures or time (exposure for the samples), and magnetic fields can be measured at various frequencies ranging from positive to negative fields. Some of the more relevant techniques used are the aforementioned low-field magnetic susceptibility (χ) and frequency dependence (χfd), which were measured at both GS1 and the three Mornington Island sites. Natural remanent magnetisation (NRM) and laboratory remanences such as anhysteretic remanent magnetisation (ARM) and isothermal remanent magnetisation (IRM) are other parameters used. Additional properties include saturation magnetisation (Ms) and saturation remanent magnetisation (Mr), saturation isothermal remanent magnetisation (SIRM), coercive force (Hc), and coercivity of remanence (Hcr), “S’ ratio and temperature (Dalan and Banerjee 1998; Dearing et al. 1996; Evans and Heller 2003; Hunt et al.

1995; Maher 1986; Thompson and Oldfield 1986). These fields can also be induced magnetisation, meaning the sample is magnetised in the presence of a magnetic field or remanent magnetisation, meaning the permanent magnetisation of a sample in the absence of an external magnetic field. Table 1 illustrates common magnetic parameters used in soil magnetic studies and how they are expressed using bivariate plots and ratios. ARM, SIRM, hysteresis loops, and high (Curie Point) and low temperature analyses were completed at GS1.

Table 1. Magnetic parameters used in archaeological studies (modified from Evans and Heller 2003: Table 2.3).

χ	Low-field susceptibility
χfd	Frequency Dependence of χ
ARM	Anhysteretic Remanent magnetisation
Ms	Saturation Magnetisation
Ms (SIRM)	Saturation Remanent Magnetisation (Saturation Isothermal Remanent Magnetisation)
IRM	Isothermal Remanent Magnetisation
Hc	Coercive Force
Hcr	Coercivity of Remanence
NRM	Natural Remanent Magnetisation
AMS	Anistropy of Magnetic Susceptibility
Bivariate Ratios S-Ratio	Soft IRM/Hard IRM
SIRM/κlf	Indicates Grain Size
ARM/SIRM	Indicates Grain Size
Hcr/Hc	Coercivity Ratio
Bivariate Plots ARM vs. χ	King Plot (Also Xarm vs. X, κarm vs. κ)
Mrs/Ms vs. Hcr/Hc	Day et al. Plot

Using various magnetic parameters involving frequency and temperature, one can characterise the magnetic mineral *composition*, *concentration* and *grain size* of a sample, all which are important in understanding magnetic minerals. Composition refers to the magnetic mineralogy and crystalline structure of the mineral (i.e. magnetite has a cubic inverse spinel structure; maghemite has a cation-deficient spinel structure), concentration refers to the mass fraction of the dominant magnetic carrier and grain size refers to the magnetic carrier's size-dependent magnetic domain. Magnetic grain sizes are small domains of uniform magnetisation (i.e. magnetic moments are aligned together) inside a grain with adjacent domains of contrasting (i.e. opposite) magnetic directions; however, when an external magnetic field is applied all magnetic directions are parallel (Figure 8). Magnetic domains are generally separated by narrow (ca 0.1 µm) domain walls (Dalan and Banerjee 1998; Mullins 1977), which vary from thermally unstable ultrafine single domains, such as super-paramagnetic (SP) grains to stable single domain (SD), to pseudo-single domain (PSD) and finally to large multidomain (MD) grains (Table 2) (Hunt et al. 1995).

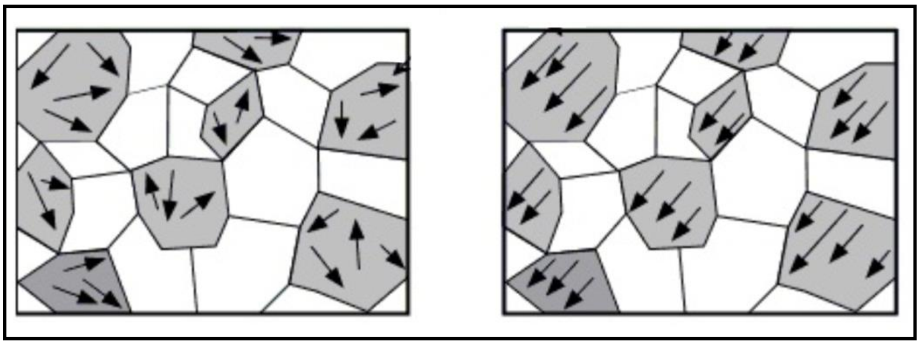

Figure 8. **Domain arrangements when unmagnetised (left), parallel alignment of domains when an external magnetic field is applied.**

Table 2. **Relative magnetic grains sizes.**

Magnetic Grain Size		Day et al. 1977	Dearing 1999
Superparamagnetic	SP	ca 0.03 µm and smaller	> 0.03 µm
Pseudo-single domain	PSD	ca 0.03–0.1 µm	ca 0.03–0.2 µm
Single domain	SD	ca 0.1–20 µm	ca 0.2–110 µm
Multidomain	MD	20 µm and greater	< 110 µm

In mineral magnetic studies, two of the most useful parameters for discerning natural soils from culturally modified soils are anhysteretic remanent magnetisation (ARM) and low-field magnetic susceptibility (χ) (Dalan and Banerjee 1998; Oldfield and Crowther 2007). ARM is an artificial magnetic remanence imparted by subjecting a sample to a strong alternating field (i.e. magnetisation in the absence of a magnetic field). This is smoothly decreased (from a peak value of 9900 Oe) to zero in the presence of a weak stead field (Banerjee 1981; Thompson and Oldfield 1986). Low-field susceptibility is induced magnetisation in the presence of a small alternating magnetic field (about 460 Hz). Plotting the two parameters together can be a quick way to discern relative grain sizes and magnetic mineralogy concentrations within stratigraphic profiles (Banerjee

1981). ARM is particularly more sensitive to finer magnetic grains like (SP) and (SD) grains while χ is more sensitive to larger (PSD) and (MD) magnetic grains (King et al. 1982).

To supplement ARM and χ data, additional magnetic studies are generally conducted. Since ARM and χ are not a direct means for measuring grain size and concentration (Dalan and Banerjee 1998) it is important to confirm their results with other magnetic studies such as S-values, hysteresis loops and high (Curie points) and low temperature tests, which provide information about magnetic grain sizes, mineralogy and concentrations. S-values offer a means for discerning soft, ferrimagnetic minerals (e.g. magnetite and maghemite) and hard, antiferromagnetics (e.g. hematite and goethite) during isothermal remanent magnetisation (IRM). IRM refers to the remanent magnetisation of a sample when exposed to steady field of a given temperature. To achieve S-values, a sample is saturated in a forward direction (SIRM) and then exposed to a backfield (i.e. equal to 0.3 T) (Dalan and Banerjee 1998; Dearing et al. 1996; Evans and Heller 2003; Thompson and Oldfield 1986). By dividing the backwards remanence by the SIRM, one can get an S-value. S-values from 0.0 to 0.5 indicate antiferromagnetic minerals, while S-values from 0.6 to 1.0 indicate ferrimagnetic minerals.

Hysteresis loops are created by imparting a sample to a cycle of increasing and decreasing magnetic fields (Figure 9). A strong magnetic field is first applied causing saturated magnetisation (Ms) on the sample. This is followed by decreasing the field back to zero. Since magnetisation does not fall back to its origin, the sample is left with a saturation remanent magnetisation (Mr). If the field is increased in a negative direction (reversed), magnetisation changes again causing a coercive force (Hc). When this negative field is decreased back to zero, the sample is left a coercivity of remanence (Hcr). Changes in the magnetised lag of these applied fields result in hysteresis (Banerjee 1981; Evans and Heller 2003; Thompson and Oldfield 1986).

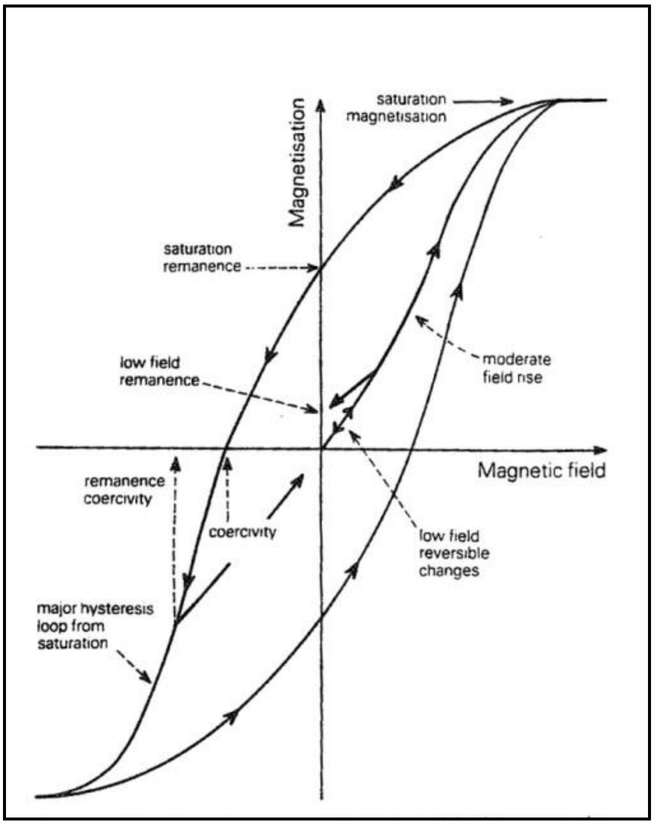

Figure 9. Magnetic hysteresis loop (Thompson and Oldfield 1986: Table 2.2).

Magnetic minerals (composition and crystal structure) can also be distinguished by high and low temperature tests. Curie points involve the measure of magnetic susceptibility by way of temperature. A sample is heated to a specific temperature and the point noted is the time magnetisation shows a rapid decrease (as it approaches zero). Temperatures above this point are known as Curie points since the sample loses its internal atomic-scale ordering (Banerjee 1981). Such tests are beneficial in that they provide information on the mineralogy. Curie points are magnetically destructive and very time consuming, therefore only selected samples are tested.

Frequency dependence (χfd) which is induced magnetisation refers to the percent difference in susceptibility when measured at two different frequencies. Readings taken at a low frequency are subtracted by readings taken at a high frequency and then divided again by the low frequency readings to provide a percentage difference in susceptibility (χfd% =(χ470Hz-χ4700Hz/χ470Hz). The difference between the measured magnetic susceptibility at low and high frequency depends on the concentration of the grains having relaxation frequencies in this interval (Neel 1949). This technique is used to investigate the contribution of ultrafine or SP magnetite grains, as they have the most pronounced frequency dependence in susceptibility (Dalan 2008; Dearing et al. 1996; Maher 1986; Thompson and Oldfield 1986). It has been shown that increases in magnetic susceptibility in conjunction with frequency dependence are indicative of either burned soils or developed surface soils, since pedogenic enhancement is typically characterised by very fine grained magnetite and maghemite (Dalan 2008; Dearing et al. 1996). Because it distinguishes these smaller grains, this technique has been used in the identification of anthropogenic sediments (i.e. burning) and buried paleosols.

Other parameters worth investigating but highly dependent on sample collection are natural remanent magnetisation (NRM) and anisotropy of magnetic susceptibility (AMS). Since rocks, sediments and soils can acquire a remanence by natural processes, NRM measurements can be applied to samples that are collected continuously from a soil column and have orientations in a particular direction noted, or before any laboratory experiments have been conducted on them. AMS also requires sample orientation to be noted since this technique is used to look at the crystalline structure or shape of the magnetic grains. AMS is the ease of magnetisation on samples that are measured at various directions.

1.4 Ground-Penetrating Radar (GPR)

The next geophysical method used for this research was GPR. GPR is a non-invasive geophysical technique that allows for the detection of buried subsurface features. This instrument is probably the most popularly recognised geophysical method in archaeology yet it is also considered one of the more complicated techniques. Its popularity largely stems from the instruments ability to map buried archaeological features in three-dimensions. This allows viewers to produce three-dimensional images of their data and in some regards a more ‘realistic’ interpretation of their site by providing spatial information both horizontally and vertically. Ironically, this ability to map in three-dimensions is one reason that makes this method so complicated as processing time can take anywhere from 2–3 days to 2–3 weeks to finalise.

1.4.1 GPR Method

GPR works by actively emitting electromagnetic energy or radar waves into the ground. When these radar waves encounter material with different contrast in the soil, such as air voids, stone or even moisture, a reflection occurs sending part of the wave back to the surface, where it is received and recorded by the instrument (Figure 10). The remainder of the radar wave continues downward until parts of it too are reflected back to the surface by deeper objects or it dissipates from being absorbed by subsurface materials. What is being measured is actually the two way travel time from the radar's antenna to a reflector and back, which is expressed as nanoseconds (nS). Mathematical calculations are able to approximate the depth at which a reflection occurred using the relationship: velocity equal distance (depth) divided by time (v = s/t) (Conyers 2004, 2012).

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) (Figure 11). Inversely, when a low frequency is applied a long wavelength is created, providing less resolution but enabling transmission of the wave much deeper (up to 8–10 m). In general, the greater the depth of investigation in a GPR survey, the lower the antenna frequency (e.g. 50–200 MHz). However, for shallow depth of investigation, the higher the antenna frequency (e.g. 400–900 MHz).

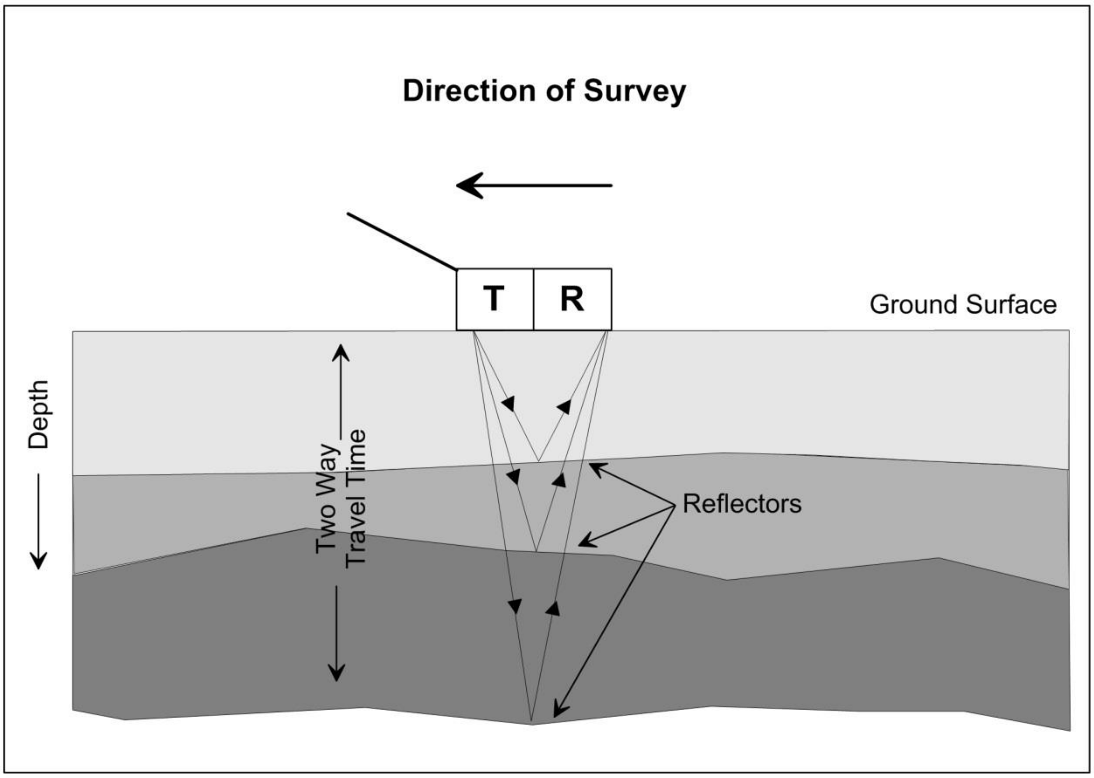

Figure 10. **GPR theory: pulsing of energy waves into the ground by the transmitter (T) which is collected by the receiver (R).**

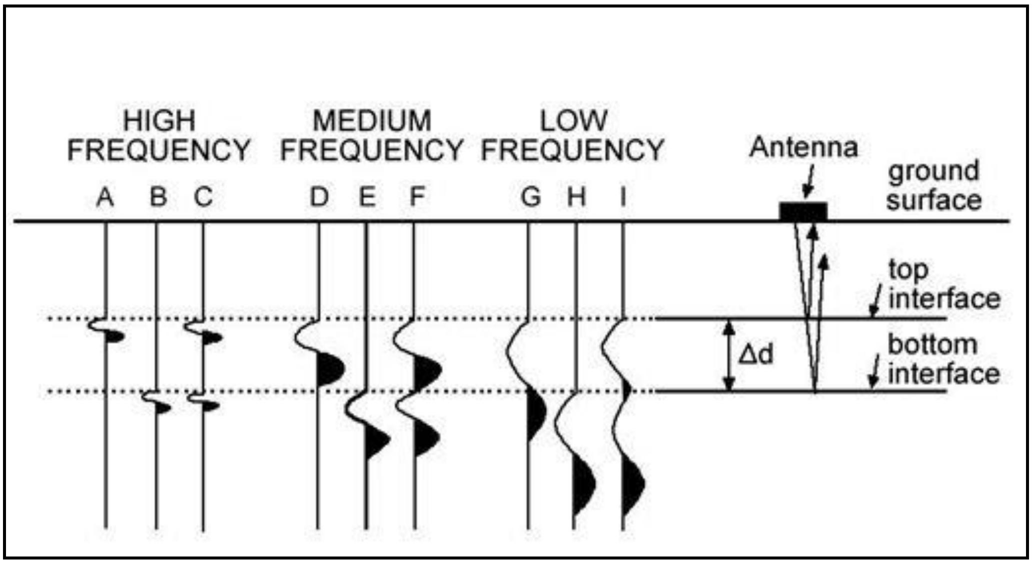

Figure 11. **Showing differences between high, medium and low frequency radar traces and depth of penetration (http://mysite.du.edu/~lconyers/SERDP/Frequency.htm).**

The propagation velocity of radar waves depends on a number of factors, the most being the electrical and chemical properties of material through which they pass, also known as relative dielectric permittivity (RDP). 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 (Table 3) (Conyers 2012; Conyers and Goodman 1997:32; Ernenwein and Hargrave 2009; Olhoeft 1981).

When there are changes between the interfaces of materials or RDP, a reflection occurs. The higher the RDP the slower the radar waves travel in that material. Other factors that can affect RDP are electrical conductivity and magnetic permeability. Highly conductive materials such as wet clays, will remove the electrical portion of the propagating waves, effectively attenuating or weakening all radar propagation. Quartz sand, which has a low conductivity and RDP will do the opposite and allow radar energy to propagate with depth at a high velocity. Changes in RDP at buried interfaces are primarily the difference in electrical properties between two materials.

Table 3. Electromagnetic properties of geological media (after Davis and Annan 1989)

Material	Dielectric constant	Conductivity (mS/m)	Velocity (m/ns)	Attenuation (dB/m)
Air	1	0	0.3	0
Distilled water	80	0.01	0.033	0.002
Fresh water	80	0.5	0.033	0.1
Sea water	80	30,000	0.01	1,000
Dry sand	3–5	0.01	0.15	0.01
Saturated sand	20–30	0.1–1.0	0.06	0.03–0.3
Limestone	4–8	0.5–2	0.12	0.4–1
Shale	5–15	1–100	0.09	1–100
Silt	5–30	1–100	0.07	1–100
Clay	4–40	2–1,000	0.06	1–300
Granite	4–6	0.01–1	0.13	0.01–1
Salt (dry)	5–6	0.01–1	0.13	0.01–1
Ice	3–4	0.01	0.16	0.01

1.4.2 Processing and Instrumentation

Reflected pulses of radar energy recorded by the receiver antenna are defined as a radar trace and are represented as a single irregular sinusoid (Figure 12a). Each radar trace contains over hundreds of samples and as it moves along the ground surface. A set of these traces are collected and placed next to one another to form a radar gram or reflection profile (Figure 12b). Reflection profiles are two-dimensional cross sections of transect data (line of collected data) containing stratigraphic information. Amplitudes that are strong are often depicted by black, weaker amplitudes are shown in white. For many decades, reflection profiles were the only way to interpret GPR data and plan-view maps were made by interpreting the location and depth of the reflections in each profile and plotting these manually by hand (Conyers and Goodman 1997).

Advance software programs have provided a way to merge reflection profiles at defined depths to create amplitude or time/depth slices of the data, providing a map or ‘slice’ of subsurface deposits (Figure 13a). Such data can also be constructed into three-dimensions, making it especially good for mapping soil compaction, structural features and void spaces, both of which are particularly pertinent in archaeological deposits (Figure 13b). Several software programs have made it possible to process GPR data and perform functions such as noise removal, reflection migration and depth determination. Others have provided more advanced processing functions such as isosurface rendering, topographic correction or overlay analysis which allows for targeted features at different depths to be easily displayed (Goodman and Piro 2013).

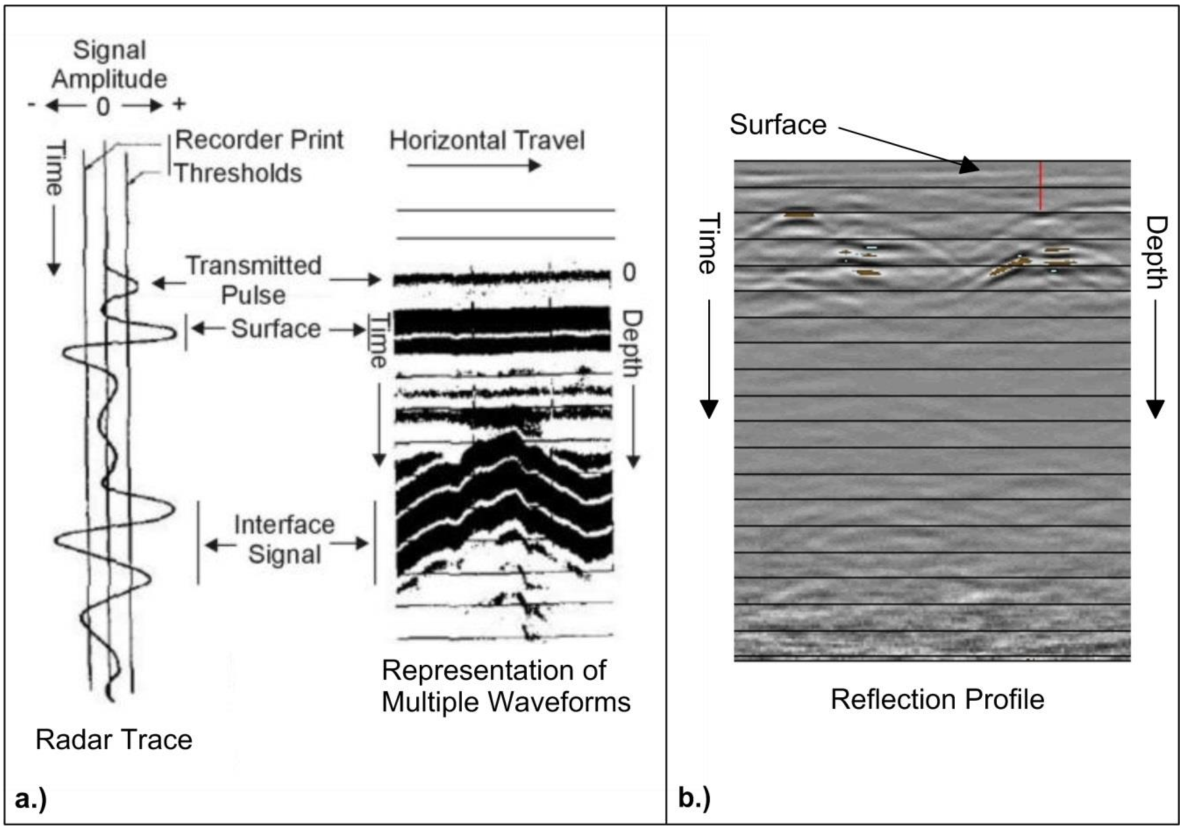

Figure 12. Single radar trace and series of combined traces for (a) and reflection profile or radar gram of GPR data(b) (modified from Benson et al. 1983).

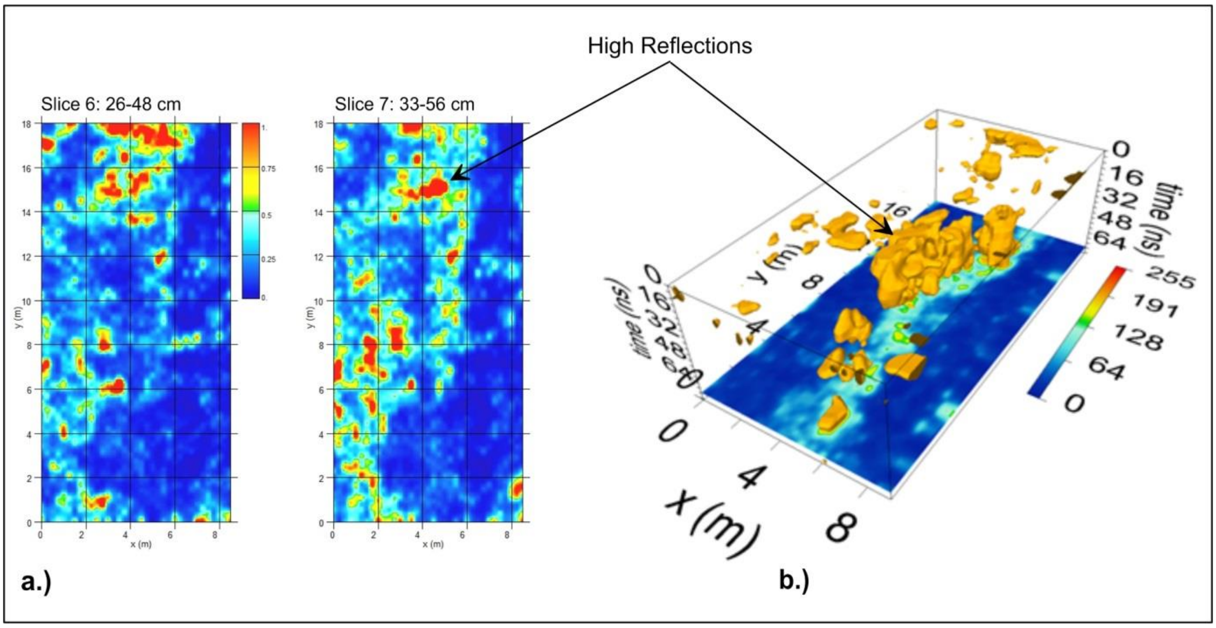

Figure 13. GPR radar or amplitude slice-maps (a) and (b) isosurface rendering superimposed on a three-dimensional slice cube. Note red and yellow (left) and yellow (right) indicate high reflections.

There are several instruments that allow for the collection of GPR data. Some of the more popular ones used in archaeological research include the Geophysical Survey System, Inc. (GSSI) SIR-3000 GPR, the Mala's X3M, Pro EX and Mala Mira, and the Noggin Smart Cart GPR. Other instruments include the RAMAC/GPR, Detector Duo Dad GPR and ImRa-System GPR. With technological advancements in instrumentation and software, instruments such as the Mala Mira can survey using four antennas simultaneously, providing higher resolution and a more defined image of subsurface features.

1.5 Other Techniques

1.5.1 Geoarchaeology

Geoarchaeological approaches have become increasingly important in the interpretation of archaeological sites, mainly because it uses any earth-science or geoscience concept, technique or knowledge to the study of archaeology (Holliday 2004; Rapp and Hill 1998; Waters 1992; Wilkinson and Stevens 2003). Encompassing a broad range of geoscience disciplines and subfields, such as stratigraphy, sedimentology, pedology, geochemistry, geophysics, geochronology and geomorphology, geoarchaeology studies the site's past depositional environment or stratigraphic layers through either its sedimentation or soils. Sedimentation, are deposits resulted from weathering. They include the transportation, erosion and deposition of particles from either local or outside sources (endogenous and exogenous), as well as post-depositional alternation, which include changes in soil formation. Soils; however, form in stable environments and contain *in situ* weathering of existing soil deposits, often referred to as the parent material. Both are important in understanding site formation and post-depositional processes as they can provide insights into the events involving human occupation patterns (i.e. site occupation and abandonment).

At any archaeological site, the main constituent for encasing and preserving the archaeological material altogether is either soil or sediments (Holliday 2004). While always not often appreciated as the material which archaeologists discover, their occurrence is exceptionally important, as they play a crucial role in understanding both the natural and cultural landscape. By examining soils (sediments) in detail, the archaeologists can begin to comprehend the stratigraphic record of a site, and in the case of rockshelters and shell middens, this is extremely important. There are a number of ways to examine soils (sediments), with the basic being those observed firstly in the field, using standard texture (sand, silt and clay), structure (granular), hue (Munsell colour), sphericity and roundness (Powers 1953), sorting (Folk's 1974) and shape (Wentworths 1922). More detailed analysis of sediments can then be conducted in a lab using instruments that can either quantify the amount of material within a sample or determine mineralogy, and instruments that can be used to look mircrospcopically at the shape, size and sorting of the sample themselves or mircromorphologically, which can be used to determine the formation processes of anthropogenic, pedogenic and geogenic materials.

Biogeochemical studies which include phosphorous (P) are also good in archaeology because they can be used to indicate human activities at a site, and determine horizontal and vertical boundaries of sites and features. One way of human activities to alter the soil environment is by adding trace amounts of metals and hydrocarbons (Holliday and Gartner 2007; Rapp and Hill, 1988). Three distinct fractions of phosphorous can be obtained and include: 1) easily extractable, mainly aluminum and iron phosphate, which is associated with growing plants; 2) more tightly bound phosphate, associated with human activity; and 3) natural geologic phosphate (Rapp and Hill 1998: 195).

To supplement the geophysical data, several other techniques were used as part of the archaeological, geophysical and sedimentological interpretation. Geoarchaeological investigations of sediment analyses involving particle size, soil texture and micromorphology, along with wood charcoal, phytolith, stone artefact and shell analysis, and loss on ignition (LOI) were completed for this thesis by the author or with other collaborators on the GS1 and Mornington Island sediments. Soil chemical studies assessing basic elements including phosphorous (P) and soil pH, geochronological applications using Accelerated Mass Spectrometer (AMS) and Optical Stimulated Thermoluminescence (OSL) dating were also completed. Correlations between the geoarchaeological, soil chemistry and magnetic susceptibility with stone artefact analysis were assessed to help verify cultural from natural inputs into the archaeological deposits. For detailed information on these methods please refer to Chapters 3, 4 and 6.

References

Banerjee, S. K. 1981 Experimental methods of rock magnetism and paleomagnetism. In B. Saltzman (ed.), *Advances in Geophysics, Vol. 23*, pp. 25–99. New York: Academic Press.

Bellomo, R. V. 1993 A methodological approach for identifying archaeological evidence of fire resulting from human activities. *Journal of Archaeological Science* 20:525–553.

Benson, R. C., R. A. Glaccum and M. R. Noel 1983 *Geophysical techniques for sensing buried wastes and waste migration*. Los Vegas: Environmental Monitoring Systems Laboratory, Office of Research and Development, U. S. Environmental Protection Agency.

Bevan, B. W. 1998 *Geophysical Exploration for Archaeology: An Introduction to Geophysical Exploration*. Midwest Archaeological Centre Special Report No. 1. Lincoln: National Park Service, Midwest Archaeological Centre.

Clark, A. 1996 *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Routledge.

Conyers, L. B. 2004 *Ground-Penetrating Radar for Archaeologists*. Walnut Creek: AltaMira.

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

Conyers, L. B. and D. Goodman 1997 *Ground-Penetrating Radar: An Introduction for Archaeologists.* Walnut Creek: AltaMira.

Dalan, R. A. 2001 A magnetic susceptibility logger for archaeological application. *Geoarchaeology* 16(3):263–273.

Dalan, R. A. 2006 A geophysical approach to buried site detection using down-hole susceptibility and soil magnetic techniques. *Archaeological Prospection* 13(3):182–206.

Dalan, R. A. 2008 A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: Recent developments and prospects. *Archaeological Prospection* 15:1–31.

Dalan, R. A. and S. Banerjee 1998 Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13(1):3–36.

Dalan R. A., S. L. DeVore and R. B. Clay 2010 Geophysical identification of unmarked historic graves. *Geoarchaeology* 25: 572–601.

Davis, J. L. and A. P. Annan 1989 Ground penetrating radar for high resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting* 37:531–551.

Dearing, J. A. 1999 *Environmental Magnetic Susceptibility: Using the Bartington MS2 System.* Kenilworth: Chi Publishing.

Dearing, J. A., K. L. Hay, S. M. J. Baban, S. A. Hudleston, E. M. H. Wellington and P. J. Loveland 1996 Magnetic susceptibility of soil: An evaluation of conflicting theories using a national data set. *Geophysics Journal International* 127:728–734.

Ding, Z., S. Xiong, J. M. Sun, S. L. Yang, Z. Y. Gu and T. S. Liu 1999 Pedostratigraphy and paleomagnetism of a ~7.0 Ma eolian loess–red clay sequence at Lingtai, Loess Plateau, north-central China and the implications for paleomonsoon evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology* 152:49–66.

Dunlop, D. J., and Ö. Özdemir 1997 *Rock Magnetism*. Cambridge: University Press.

Ellwood, B., F. B. Harrold, S. L. Benoist, P. Thacker, M. Otte, D. Bonjean, G. J. Long, A. M. Shahin, R. P. Hermann and F. Grandjean 2004 Magnetic susceptibility applied as an age-depth-climate relative dating technique using sediments from Scladina Cave, a late Pleistocene cave site in Belgium. *Journal of Archaeological Science* 31(3):283–293.

Ellwood, Brooks B., D. E. Peter, W. Balsam and J. Schieber 1995 Magnetic and geochemical variations as indicators of palaeoclimate and archaeological site evolution: Examples from 41TR68, Fort Worth, Texas. *Journal of Archaeological Science* 22(3):409–415.

Ellwood, B. B., K. M. Petruso, F. B. Harrold and J. Schuldenrein 1997 High-resolution paleoclimatic trends for the Holocene identified using magnetic susceptibility data from archaeological excavations in caves. *Journal of Archaeological Science* 24:569–573.

Ernenwein, E. G. and M. L. Hargrave 2009 *Archaeological Geophysics for DoD Field Use: A Guide for New and Novice Users*. ESTCP Project SI-0611. United States Department of Defence: Environmental Security Technology Certification Program.

Evans, M. E. and F. Heller 2003 *Environmental Magnetism: Principles and Applications of Enviromagnetics*. London: Academic Press.

Fassbinder, J. W. E., H. Stanjek and J. Vali 1990 Occurrence of magnetic bacteria in soil. *Nature* 343:161–163.

Fischer, W. R. 1988 Microbiological reactions of iron in soils. In J. W. Stucki, B. A. Goodman and U. Schwertmann (eds), *Iron in Soil and Clay Minerals*, pp. 715–748. Dordrecht: Reidel Publishing.

Fitzpatrick, R. W. 1985 Iron Compounds as Indicators of Pedogenic Processes: Examples from the Southern Hemisphere. In J. W. Stucki, B. A. Goodman and U. Schwertmann (eds), *Iron in Soil and Clay Minerals, Vol. NATO ASI Series C 217*, pp. 351–396. Dordrecht: Reidel Publishing.

Folk, R. L. 1954 The distinction between grain size and mineral composition in sedimentary-rock nomenclature: *The Journal of Geology* 62(4): 344–359.

Frahm, E. and J. M. Feinberg 2013 From flow to quarry: magnetic properties of obsidian and changing the scale of archaeological sourcing. *Journal of Archaeological Science* 40(10):3706–3721.

Gaffney, C., and J. Gater 2003 *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus Publishing Ltd.

Goodman, D., and S. Piro 2013 *GPR Remote Sensing in Archaeology*. New York: Springer.

Herries, A. I. R. and A. G. Latham 2009 Archaeomagnetic studies at the Cave of Hearths. In J. McNabb and A. G. M. Sinclair (eds), *The Cave of Hearths: Makapan Middle Pleistocene Research Project, University of Southampton Series in Archaeology*, pp. 59–64. Oxford: Archaeopress.

Herries, A.I. R. 2006 Archaeomagnetic evidence for climate change at Sibudu cave. *South African Humanities* 18:131–147.

Herries, A. I. R. and E. C. Fisher 2010 Multidimensional GIS modelling of magnetic mineralogy as a proxy for fire use and spatial patterning: evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution* 59(3–4):306–20.

Holliday, V. T. 2004 *Soils in Archaeological Research*. Oxford: Oxford University Press.

Holliday, V. T. and W. G. Gartner 2007 Methods of soil P analysis in archaeology. *Journal of Archaeological Science* 34:301–333.

Hunt, C. P., B. M. Moskowitz and S. K. Banerjee 1995 Magnetic properties of rocks and minerals. In T. J. Ahrens (ed.), *Rock Physics and Phase Relations: A Handbook of Physical Constants*, pp. 189–204. AGU Reference Shelf 3. Washington D. C.: American Geophysical Union.

Johnson, J. K. (ed.) 2006 *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Tuscaloosa: University of Alabama.

Jordanova, N., E. Petrovsky, M. Kovacheva and D. Jordanova 2001 Factors determining magnetic enhancement of burnt clay from archaeological sites. *Journal of Archaeological Science* 28:1137-1148.

Keys, B. O. 2009 *Engrained in the Past: Using Geoarchaeology to Understand Site Formation Processes at the Gledswood Shelter 1 Site, Northwest Queensland.* Unpublished BA (Honours) thesis, Department of Archaeology, Flinders University, Adelaide.

King, J. W., S. K. Banerjee, J. Marvin and Ö Özdemir 1982 A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: Some results in lake sediments. *Earth and Planetary Science Letters* 59:404–419.

Le Borgne, E. 1955 Susceptibilite magnetiqe anormale de sol superficiel. *Annales de Geophysique* 11:399–419.

Le Borgne, E. 1960 Influence de feu sur les proprietes magnetiques du sol et sur celles du schist et du grantie. *Annales de Geophysique* 16:159–195.

Le Borgne, E. 1965 Les proprites magnetiques du sol. Application a la prospection des sites archeologiques. *Archaeo-Physika* 1:1–20.

Linford, N. and E. Platzman 2004 Estimating the approximate firing temperature of burnt archaeological sediments through an unmixing algorithm applied to hysteresis data. *Physics of the Earth and Planetary Interiors* 147(2–3):197–207.

Linford, N. 2005 Archaeological applications of naturally occurring nanomagnets. *Journal of Physics: Conference Series* 17:127–144.

Linford, N. T., P. Linford and E. Platzman 2005 Dating environmental change using magnetic bacteria in archaeological soils from the upper Thames valley, United Kingdom. *Journal of Archaeological Science* 32(7):1037–1043.

Longworth, G. and M. S. Tite 1977 Mossbauer and magnetic susceptibility studies on iron oxide in soils from archaeological sites. *Archaeometry* 19:3–14.

Lowe, K. M. and A. S. Fogel 2010 Understanding Northeastern Plains village sites through archaeological geophysics. *Archaeological Prospection* 17:247–257.

Maher, B. A. 1986 Characterisation of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interior* 42:76–92.

Maher, B. A. and M. W. Houslow 1999 The significance of magnetotactic bacteria for the palaeomagnetic and rock magnetic record of Quaternary sediments and soils. In D. H. Tarling and P. Turner (eds), *Palaeomagnetism and Diagenesis in Sediments*, pp. 43–46. London: Geological Society Special Publications 151.

Maher, B. A. and R. M. Taylor 1988 Formation of ultrafine-grained magnetite in soils. *Nature* 336:368–371.

Maki, D. 2005 Lightning strikes and prehistoric ovens: Determining the source of magnetic anomalies using techniques of environmental magnetism. *Geoarchaeology* 20(5):449-459.

Marmet, E., M. Bina, N. Fedoroff and A. Tabbagh 1999 Relationships between human activity and the magnetic properties of soils: a case study in the medieval site of Roissy-en-France. *Archaeological Prospection* 6(3):161–170.

Marwick, B. 2005 Element concentrations and magnetic susceptibility of anthrosols: Indicators of prehistoric human occupation in the inland Pilbara, Western Australia. *Journal of Archaeological Science* 32:1357–1368.

Milani, J. L. 2010 *Unveiling Rock Art Images: A Pilot Project Employing a Geophysical Technique to Detect Magnetic Signatures*. Unpublished MArch Thesis, Department of Archaeology, Flinders University, Adelaide.

Moffat, I., L. A. Wallis, M. W. Hounslow, K. Niland, K. Domett and G. Trevorrow 2010 Geophysical prospection for late Holocene burials in coastal environments: Possibilities and problems from a pilot study in South Australia. *Geoarchaeology* 25(5):645–665.

Mooney, S, C. Geiss and M. A. Smith 2003 The use of mineral magnetic parameters to characterize archaeological ochres. *Journal of Archaeological Science* 30:511–523.

Mullins, C. E. 1977 Magnetic susceptibility of the soil and its significance in soil science - A review. *Journal of Soil Science* 28(2):223–246.

Mullins, C. and M. S. Tite 1973 Preisach diagrams and magnetic viscosity phenomena for soils and synthetic asseblies of iron oxide grains. *Journal of Geomagnetism and Geoelectrictiy* 25:21–229.

Neel, L. 1949 Theorie du trainage magnetique des ferromagnetiqes en grains fin avec application aux terres cuites. *Annales de Geophysique* 5:99–136.

Oldfield, F., K. Tolonen and R. Thompson 1981 Artificial enhancement of stream bedload: A hydrological application of superparamagnetism. *Physics of the Earth and Planetary Interiors* 26:107–124.

Oldfield, F. and J. Crowther 2007 Establishing fire incidence in temperate soils using magnetic measurements. *Palaeogeography, Palaeoclimatology, Palaeoecology* 249:362–369.

Olhoeft, G. R. 1981 Electrical properties of rocks. In Y. S. Touloukian, W. R. Judd and R. F. Roy (eds), *Physical Properties of Rocks and Minerals*, pp. 257–330. New York: McGraw-Hill.

Powers, M. C. 1953 A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology 23*:117–119.

Rapp, G. R. Jr. and C. L. Hill 1998 *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.

Reynolds, J. M. 1997 *An Introduction to Applied and Environmental Geophysics*. John Wiley and Sons Ltd, Chichester.

Rosendahl, D., K. M. Lowe, A. Fogel, J. Budby, J. Budby, L. A. Wallis and E. Oliver 2013 Mapping the invisible: Using magnetic susceptibility to assist in hearth salvage and site mapping on a mine site in Central Queensland. Paper presented at the Australian Archaeological Association Annual Conference, Coffs Harbor, Australia.

Scollar, I. 1971 A magnetometer survey of the Colonia Ulpin Trajana near Xantern, west Germany. Prospezioni *Archeologiche* 6:83–92.

Scollar, I., A. Tabbagh, A. Hesse and I. Herzog 1990 *Archaeological Prospecting and Remote Sensing*. Cambridge: Cambridge University Press.

Taylor, R. M., B. A. Maher and P. G. Self 1987 Magnetite in soils: I. The synthesis of single-domain and superparamagnetic magnetite. *Clay Minerals* 22:411–422.

Thacker, P. T. and B. B. Ellwood 2002 The magnetic susceptibility of cherts: Archaeological and geochemical implications of source variation. *Geoarchaeology* 17(5):465–482.

Thompson, R. and F. Oldfield 1986 *Environmental Magnetism*. London: Allen and Unwin.

Tite, M. S. 1972a The influence of Geology on the magnetic susceptibility of soils on archaeological sites. *Archaeometry* 14:229–236.

Tite, M. S. 1972b *Methods of Physical Examination in Archaeology*. London: Seminar Press.

Tite, M. S. and C. Mullins 1971 Enhancement of the magnetic susceptibility of soils on archaeological sites. *Archaeometry* 13(209–219).

Waters, M. R. 1992 *Principles of Geoarchaeology: A North American Perspective*. Tucson: The University of Arizona Press.

Wilkinson, K. and C. Stevens 2003 *Environmental Archaeology: Approaches, Techniques and Applications.* Gloucestershire: Tempus Publishing.

Witten, A. J. 2006 *Handbook of Geophysics and Archaeology*. London: Equinox Publishing.

Wentworth, C. K. 1922 A scale of grad and class terms for clastic sediments. *The Journal of Geology* 30(5):377–392.

West, G. F. and J. C. Macnae 1991 Physics of the Electromagnetic Induction Exploration Method. In M. N. Nabighian and E. B. Neitzel (eds), *Electromagnetic Methods in Applied Geophysics*. pp. 5–45. Tulsa: Society of Exploration Geophysics.

United States Environmental Protection Agency (EPA) 1993 *Electromagnetic Induction Principles*. Ohio: Office of Solid Waste and Emergency Response.

APPPENDIX B

MASTER DATA FOR GLEDSWOOD SHELTER 1

(See supplementary data – CD insert in back)

APPPENDIX C

IRM DATA FOR GLEDSWOOD SHELTER 1

(See supplementary data – CD insert in back)

APPPENDIX D

MASTER DATA FOR MORNINGTON ISLAND: GUTTAPERCHA, MALA KATHA AND MUNBURLDA

(See supplementary data – CD insert in back)