



Using Advanced Remote Sensing Technologies
to Discriminate Patterns
of Ancient Aboriginal Land Use
in the Australian Arid Zone

by

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*For Sarah and Kiva,
Who urged me to get out of the office
and spend more time at the beach.*

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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I acknowledge the support and funding I have received for my research through the provision of the Australian Government Research Training Program Scholarship. I am also the recipient of the University of Adelaide Faculty of Sciences Divisional Scholarship and the Constance Fraser Supplementary Scholarship, which have additionally supported me throughout my PhD candidature.

Abstract

There is a long-standing perception amongst some scholars in the Australian archaeological community that aerial and satellite remote sensing technologies have little to offer researchers because, in general, the imagery derived from such platforms is not of sufficient spatial resolution to detect and identify the architectural structures, cultural features or landscape modifications made by ancient Aboriginal peoples. This thesis suggests this perception is unjustified, and it argues that remote sensing can provide valuable information on the distribution of natural resources, which is important for understanding the archaeological record of Australia. Thus, rather than focusing on how remote sensing technologies can be used to detect how Aboriginal Australians transformed the environment, this research proposes that remote sensing should be used to investigate how precontact forager groups interacted with the natural environment itself.

The past three decades of Australian archaeological research has placed particular emphasis on human ecology and in particular, how the location of water, plant communities and stone resources are important for understanding traditional Aboriginal subsistence and settlement practices in Australian arid zone. This type of information is important for understanding where particular kinds of archaeological sites may occur and how people positioned themselves amongst natural resources in an environmentally varied desertic landscape. The arid land systems of central and western Australia offer an ideal context to investigate the archaeological record with remote sensing technologies, as these sparsely vegetated arid environments provides ample opportunity to obtain bare-earth observations of natural resources with satellite and aerial imagery. These characteristics are ideal for assessing the usefulness of a wide range of forms of remote sensing and exploring the overarching theme of this thesis—the relevance of advanced remote sensing technologies for our understanding of past Aboriginal land use and site distribution in the Australian arid zone.

In this thesis, it is shown how many kinds of remotely sensed information are useful to the investigation of the Aboriginal archaeological record. The research is presented in three case studies, each leading to a changed perception and understanding of the archaeological record informed by use of aerial and satellite remote sensing investigations. The first case study demonstrates how satellite-derived digital elevation data can be used to construct a digital terrain model,

offering a more objective interpretation of the land units in which stone arrangement sites are likely to be constructed. The second example uses airborne hyperspectral imagery to map silicified rock sources, showing how spectral analysis can be used to discriminate where potential 'tool-stone' could be procured for artefact manufacture. The third case study shows how multiple remote sensing and geospatial datasets can be combined to model habitat suitability across the Western Desert of Australia, testing previous models of human ecology in a detailed way that previous landscape analyses could not. The outcomes of this research allow us to better understand a greater range of Aboriginal subsistence and settlement practices in this vast arid region.

The thesis concludes with the recognition that environmental remote sensing has much to offer Australian archaeological research, and the discipline seems to be on the cusp of a technological revolution. In recent years, an increasing diversity of remotely sensed information has become readily accessible, with many data sources providing open access through numerous online platforms and cloud-based processing systems. It is predicted that the future of Australian archaeology is poised for a period of substantial growth and development of applied remote sensing research, which will only be hindered by a lack of interdisciplinary awareness and spatial science training opportunities.

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Reflecting on all the things that have happened during the time frame of this degree, I am amazed that I'm actually finishing my PhD on time. So many things have come to pass over the past four years. My wife, Sarah, and I cared for a baby and took time out to build a 90m² three bedroom extension onto our 'little' stone house—doing nearly all of the stonemasonry and labour ourselves. We watched our gorgeous daughter, Kiva, grow into a clever, confident and empathetic five-year-old. We lived through a horrific summer of bushfires and did what we could to help our beloved Kangaroo Island community. And now, as I submit this thesis, we face what is believed to be only the beginning of the COVID-19 health crisis. What a crazy time it has been!

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The completion of this thesis represents a major personal goal for me. Working with satellite imagery and the archaeological record is something that I have been inspired to do ever since reading an *OMNI* magazine article about "How satellites found a lost Mayan city" when I was 12 years old. In this regard, I should thank my parents, Ken and Carol Law, for fostering my childhood interest in space and archaeology. And I should also thank my little sister, Julie, for tolerating my big brotherly interests in Space Camp and Indiana Jones movies. I also appreciate the influences and opportunities afforded on me by my aunt and uncle, Carol Law and

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About the Author

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In 2015, the University of Adelaide awarded him the Faculty of Sciences Divisional Scholarship and the Constance Fraser Supplementary Scholarship to undertake a PhD in Environmental Remote Sensing and Geospatial Science in the School of Biological Sciences. His research is also supported through a provision of the Australian Government Research Training Program Scholarship. He is a member of the University of Adelaide's Spatial Science Group, an interdisciplinary research group within the Department of Ecology and Evolutionary Biology. His PhD research focuses on the application of aerial and satellite remote sensing technologies to investigate past Aboriginal land use and archaeological site distribution in the Australian arid zone. During his candidature, the outcomes of his PhD research have been published in the peer-reviewed international journals *Archaeological Prospection* and *Geoarchaeology: An International Journal*.

Mr. Law has additionally collaborated on a number research articles with colleagues at Scarp Archaeology Pty Ltd, where in recent years they have published in the journals *Australian Archaeology*, *Archaeology and Oceania*, *Journal of Field Archaeology* and *Quaternary Science Reviews*. Through his connection as a Senior Archaeologist with Scarp, he is an Associate Investigator with the Australian Research Council Centre of Excellence for Biodiversity and Heritage (CABAH) at James Cook University. He is also the former Secretary of the Australian Archaeological Association, serving for two years in 2018 and 2019.

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Chapter 1 Introduction

This thesis explores how advanced aerial and satellite remote sensing can be used to investigate and interpret the archaeological record of the Australian arid zone. It begins with the simple consideration of why, for more than four decades, Australian archaeologists have largely ignored the usefulness of the aerial and satellite imagery. The work then goes on to explore how advanced remote sensing methodologies can be used as scientific tools to investigate and reveal new information about ancient Aboriginal land use and the nature of the early, pre-contact Australian archaeological record. It achieves this via the presentation of three novel case studies that show how the spatial patterns and information revealed through remote sensing can considerably change our understanding of Australia's ancient Aboriginal past.

This chapter provides a brief introduction to the study and frames the context of my research. The aims and objectives of the thesis are presented (section 1.1) and a brief background is provided on the remote sensing knowledge gap that exists in contemporary Australian archaeology (section 1.2). The research questions that guide this study are discussed (section 1.3), and the significance, novelty and potential impacts of using remote sensing for Aboriginal archaeological applications are discussed (section 1.4). The closing section outlines how the remaining chapters of this thesis are organised (section 1.5).

1.1 AIM AND PURPOSE

The chief aim of my PhD research is to investigate and reveal how our understanding of ancient Aboriginal land use concepts can be considerably improved by utilising advanced methods in environmental remote sensing. Here, it is proposed that remote sensing, as a scientific discipline, offers refreshing analytical perspectives for improving our knowledge of past landscapes, environmental patterns and geography, which are all invariably linked to our interpretation of the Aboriginal archaeological record. I argue that the integration of remote sensing and geospatial analysis with archaeological research will lead to a better understanding of past land use practices and archaeological site distribution in Australia's vast desert regions.

Archaeologists have long contended that the ancient populations of Australia's deserts had a strong familiarity with the distribution of natural resources (Gould,

1969, 1977, 1980; Gould & Saggars, 1985; Hiscock, 2008; Hiscock & Wallis, 2005; Smith, 1993; Smith, 1996). Ancestral Aboriginal peoples understood the landscape contexts where water, stone and plant communities were likely to be found and, in many instances, traditional knowledge of prominent desert resource localities was multigenerational. Reciprocal knowledge was shared amongst individuals in home and neighbouring territories. Given the importance of resource access in a high-risk arid landscape, it is understandable why every ecological model of past Aboriginal subsistence and settlement of the arid zone has considered the distribution of archaeological sites in relation to natural resources, but the information supporting this has largely remained conceptual and not spatially quantified in any detailed way. The information used to characterise past Aboriginal land use is generally derived from a highly varied combination of ecological ideas, principally based on ethnographic observations, archaeological site data, palaeoclimatic studies, biogeographical features, and other environmental characteristics. While this information is quite useful, it is important to recognise that it is typically applied coarsely, meaning that it is often generalised and broadly applied to loosely-defined areas of the landscape. This information lacks a finer, more nuanced understanding of how people may have utilised and behaved in relation to resource distribution and land characteristics. In this regard, modern spatial science has much to offer, as there is now a multitude of satellite and aerial information available that can provide finer-grained details to better understand past patterns of land use than earlier studies.

With the exception of a few recent examples (Bird et al., 2016; Bliege Bird et al., 2008), processed Earth observation data and spatially quantified landscape characteristics have not been overtly integrated with the prominent archaeological interpretations of Aboriginal land use so, in this sense, the advanced remote sensing methods employed in the PhD are novel in their approach to investigating the Australian archaeological record. Thus, much of the purpose of this research is to demonstrate a wide range of remote sensing applications that may be integrated with geospatial analysis to improve our understanding of ancient Aboriginal land use.

1.2 BACKGROUND

The promise of remote sensing is awesome. But its full potential will be realized only as archaeologists transcend the seductive gadgetry to integrate this technology into the mainstream of archaeological theory.

-Thomas (1989, p. 237)

Geospatial technologies are increasingly important for managing and directing archaeological research. While many researchers may consider global positioning systems (GPS) and geographical information systems (GIS) to be ‘mainstream’ geospatial tools, the use of advanced aerial and satellite remote sensing image products to investigate the Australian archaeological record is uncommon. Most researchers have casually accessed aerial and satellite imagery in free software programs like Google Earth Pro™, so there is some familiarity with Earth observation imagery in the community. However, few archaeological professionals possess the advanced skills to manipulate and extract information from the remotely sensed imagery and benefit from the full investigative potential of remote sensing products. Additionally, since most archaeologists are not formally trained as spatial scientists, there is a lack of knowledge of what might be possible with sophisticated imagery data and how this information may be useful to their research.

Remote sensing has developed over the past 50 years into a diverse and highly specialised discipline. It is grounded by a well-established international network of professional associations, research institutes, journals, books and technical manuals dedicated to the subject. As a discipline, it has reached a level of maturity that attracts interest from many scientific communities, and it is an area of research that is continuously expanding through new applications, technological advancements and innovations.

The effective application of remote sensing methods and data analysis requires an advanced understanding of the physical principles underpinning the interaction of electromagnetic radiation with Earth surfaces and of the nature of the data collected by an increasing diversity of platforms and sensors. Specialist analytical skills and software are required to process the raw imagery into meaningful information and maps. Remote sensing shares some spatial principles and software with conventional GIS studies, and there is little question that the disciplines are closely related; however, remote sensing differs in that it involves the measurement and collection of new information about Earth surface phenomena using sensors mounted on a variety of platforms such as satellites, aircraft, balloons, and,

increasingly, drones. To measure and obtain remotely sensed information, there is no physical interaction with the material: the measurements are acquired from afar, or 'remotely'. Conversely, the emphasis of GIS is on the integration, analysis and presentation of many forms of spatial data to map, model and understand geographic relationships. Georeferenced imagery acquired from remote sensing may be opened and manipulated (with limitations) in most GIS software packages, so it is a complementary tool for visualising and integrating remote sensing data with other forms of spatial data.

Thus, remote sensing is a highly specialised endeavour, and the knowledge required to select, source, process and interpret remotely sensed imagery is a barrier for most archaeologists, which partially explains why Australian researchers rarely integrate remote sensing products into their projects. The other perceived drawback is that the cost of commercial imagery is often high, far exceeding most project budgets. Despite this, there is an increasing number of free, open access or inexpensive products available from government and industry sources that position remote sensing to become more accessible to researchers.

The archaeological community's general unfamiliarity with remote sensing is further juxtaposed by an underlying assumption that remote sensing is not applicable to Aboriginal studies. As recognised and discussed by Connah and Jones (1983), some investigators do not see the relevance of aerial archaeology because the small scale of most images lacks sufficient detail to detect most Aboriginal sites or structures. This attitude may have been somewhat justified 37 years ago, but it would be incomprehensible for any modern researcher to embrace this out-dated view, particularly since the spatial, spectral, radiometric and temporal resolution of aerial and satellite imagery is continuously improving and the benefits of remote sensing for Australian archaeology are demonstrable (e.g., Bird et al., 2016; Bliege Bird et al., 2008). It is now evident, more than ever, that remote sensing is a powerful investigative tool for the natural sciences. Ecological, biological, paleontological and geological studies of the past few decades have benefitted significantly from the contribution of remote sensing. The technology is effective for habitat and landscape modelling (e.g., Aplin, 2005; De Reu et al., 2013; Kerr & Ostrovsky, 2003; Miller & Schaetzl, 2015; Riley et al., 1999; Weiss, 2001), and it presents an innovative way for accurately identifying and mapping mineralogical and biological phenomena (e.g., Anemone et al., 2011; Conroy et al., 2012; Lewis, 2000; Lewis, 2002; Lewis et al., 2001). The desktop-based nature of remote sensing

analysis has also been shown to reduce unproductive field time and optimise research outcomes by targeting landforms, vegetation communities, and areas of interest prior to fieldwork (e.g., Anemone et al., 2011; Conroy et al., 2012). Thus, the benefits of remote sensing extend beyond the boundaries of research and into the realm of project management.

Undoubtedly, the benefits of modern remote sensing far outweigh any scepticism the technology may have received in the past, and remotely sensed imagery is more accessible than ever before. It is fair to observe that if remote sensing is useful to related natural sciences, then it should also be beneficial for the investigation of Aboriginal archaeology.

It is interesting that remote sensing data are not more commonly used in Australian archaeological projects, particularly since most of the continent is ideally suited for the collection of remotely sensed observations. Roughly 70 percent of the Australian land mass is arid, receiving less than 300mm of annual rainfall annually (Bureau of Meteorology 1989). The weather patterns of desert regions are more conducive to the acquisition of cloud-free imagery than tropical areas, where frequent cloud cover often interferes with image capture and quality. Similarly, the absence of dense forest canopies in the arid zone allows for relatively unobscured aerial observations of the Earth's surface. Furthermore, compared to heavily populated coastal areas, a very high proportion of the ground surface in remote arid regions has not been impacted by major earthworks or urban development. Thus, the harsh and remote nature of outback Australia affords arid zone archaeologists the opportunity to investigate Aboriginal archaeological patterns across vast and relatively undisturbed natural landscapes.

Aboriginal peoples are often regarded as having a remarkable familiarity with where natural resources occur in the landscape (e.g., water, stone, plant and animal communities), and there are many archaeological and ecological models that have been posited to explain how the spatial distribution of these resources influenced prehistoric arid land use (Gould, 1977, 1980; Hiscock, 1988, 2008; Hiscock & Wallis, 2005; Law, 2009; Smith, 1993, 2013; Smith et al., 2008; Thorley, 1998, 2001; Veth, 1989, 1993, 2005). The details of these earlier models are explored at much greater length in the following chapters of this thesis, but it is worthwhile highlighting that the distribution and abundance of natural resources is emphasised in each model. Interestingly, the use of Earth observation data is notably absent from these earlier models. Rather, they are based entirely on a combination of stone artefact data,

geology, geomorphology, biogeography, radiometric dates, palaeoclimatic studies and ethnographic observations. Together, these data sources have been synthesized to make inferences about past Aboriginal land use that continue to guide archaeological research in the arid zone today. Thus, in consideration of the scant use of aerial and satellite imagery for ecological and archaeological modelling, it appears that this is an area of research that has much to gain from remote sensing.

Despite the clear importance and emphasis of natural resource distribution in previous studies, the use of advanced remote sensing to investigate the archaeological record of Australia's desert peoples is a relatively recent phenomenon (see Bird et al., 2016). The emerging interest and scarcity of Australian archaeological studies in this area suggests that a significant knowledge gap exists, and further discussion of arid land use concepts would benefit from the objective, quantitative and spatially-explicit environmental information that remote sensing offers.

For instance, water availability has long been considered a key factor for explaining arid land use (Gould, 1977, 1980; Hiscock, 2008; Thorley, 1998, Veth, 1993). Multispectral satellite imagery offers a medium to discriminate and observe surface water inundation in desert areas, thereby measuring the spatial distribution, duration and frequency of inundation for ephemeral, semi-permanent and permanent waters. Similarly, multispectral imagery can also be used to measure the greening of desert vegetation after rainfall, providing an inference for plant resource richness and assist with the identification of suitable foraging habitats. The level of detail provided by such information allows for the refinement and systematic testing of ecological and archaeological models at scale and resolution not seen before, revealing new understandings of Aboriginal ecology and the archaeological record.

Optical remote sensing also has the ability to characterise the 'spectral signatures' of surface phenomena, which are useful for finding the provenance of raw materials used for stone artefact manufacture. Researchers often discuss the distance to non-local or 'exotic' Aboriginal 'tool-stone' as a measure of residential mobility, but the distance to the outcrop is either speculative or not definitively measured (Bird, 1985; Gould & Saggars, 1985; Law, 2009; Veth, 1993). To resolve this matter, multispectral or hyperspectral imagery can be useful for pinpointing the location of specific raw materials and substantiating distance-to-resource arguments. This information can further be used to quantify the area and

volumetrics of the resources, offering a means to quantify the economic significance of the resource.

Several remote sensing technologies also offer accurate, highly resolved records of terrain and elevation. This information is useful for modelling geomorphological and surface terrain features, which can provide valuable contextual information for understanding archaeological site setting. For example, many particular site types (e.g., artefact scatters, rockshelters, stone arrangements, or engraving sites) are more likely to occur in certain landforms or land units. Digital elevation models (DEM) derived from satellite and aerial stereoscopic imagery or LiDAR can be used to classify land units into their relative geomorphic slope position and classify terrain attributes. The resulting digital terrain model can be used to investigate the distribution of archaeological site by landform; thus, creating a more spatially informed study of Aboriginal land use.

Airborne and spaceborne remote sensing products have been widely used in the natural sciences for decades. Biology, ecology, geology, and palaeontology studies often use remote sensing products to identify the location of natural resources and application of remote sensing in these fields is well-reviewed (Anemone et al., 2011; Aplin, 2005; Conroy et al., 2012; Drury, 2001; Gupta, 2018; Horning et al., 2010; Kerr & Ostrovsky, 2003). In fact, the application of remote sensing has become so common in these disciplines that many natural science undergraduate programs offer training courses in remote sensing as part of the university curriculum. Thus, students are increasingly aware of the power and broad relevance of aerial and satellite remote sensing technologies.

With the diversity and accessibility of remotely sensed imagery products ever-increasing, it is likely that researchers are on the cusp of an intense period of interest in airborne and satellite remote sensing for Aboriginal archaeology. In anticipation of the heightened importance of archaeological remote sensing for future projects, this thesis aims to narrow the significant knowledge gap that presently exists in remote sensing applications for Australian archaeology.

1.3 RESEARCH QUESTIONS

There are few examples of remote sensing applications in Aboriginal archaeological research; hence much of the motivation for this PhD is to demonstrate the usefulness of remote sensing to an Australian archaeological audience. Aerial and satellite remote sensing for archaeology is well-established in

Europe and North America, boasting a number of overseas research centres and institutes dedicated to archaeological remote sensing. Specialists in Australian archaeological remote sensing are uncommon, and the technology has not been embraced by the archaeological community, largely due to a lack of professional training opportunities and a lack of exposure to the benefits of remote sensing technologies. My PhD research aims demonstrate how remotely sensed aerial and satellite data can be applied to better understand the Aboriginal archaeological record by presenting examples of how remote sensing can be used to investigate and interpret past Aboriginal land use and archaeological site distribution in the Australian arid zone. By doing so, this research will begin to fill the significant knowledge gap that exists for application of remote sensing technologies in Australian archaeology.

This PhD poses three principal research questions that are addressed through the following four chapters.

The first question asks, "In what contexts has remote sensing been used in Australian archaeology?" It is answered through a literature review of the history and use of aerial and satellite remote sensing technologies by Australian archaeologists, with particular reference to how Earth observation information has been used to investigate the Aboriginal archaeological record. Currently, no archaeologists have comprehensively assessed the usefulness of aerial and satellite remote sensing in Australia, so the intent of the literature review is to provide background on the history of Australian archaeological remote sensing and research directions in this area of the discipline. Importantly, the literature review highlights a long-standing perception amongst researchers that environmental remote sensing has little usefulness to investigate the Aboriginal archaeological record because the spatial resolution of the imagery is too coarse to discern cultural features or landscape modifications by ancient Aboriginal peoples. I explain how I reject this assertion by providing examples of modern Australian archaeological studies where remote sensing data have been featured prominently. It concludes by recognizing that it is only in recent times that the attitude to remote sensing has changed in this country. The catalyst for the attitude shift is most likely attributed to improved awareness and accessibility of Earth observation products, as well as widespread availability of affordable software and technologies to assist with image analysis and visualization.

The second research question asks, "How can remote sensing be used to investigate land use and archaeological site distribution in the Australian arid zone?" This question is widely explored in three original case studies, presented as separate chapters in this thesis. Each of these studies independently answer the question by providing applied examples of how remote sensing data can inform our understanding of Aboriginal land use and archaeological site distribution. The first application uses a satellite-derived DEM and geomorphometric derivatives to construct a digital land unit model to discriminate which land units stone arrangements are likely to have been constructed by earlier Aboriginal peoples. The research shows that Aboriginal stone arrangements occur in landform contexts that are contrary to previous understandings of this site type.

The second research paper uses hyperspectral sensing to investigate the distribution of potential silcrete 'tool stone' sources near Dalhousie Springs, South Australia. Silcrete was an important rock resource for past Aboriginal populations. Since silcrete typically forms through secondary diagenetic geological processes (e.g., duricrust), the provenance of silcrete is not always on geological maps and sources are often unknown; therefore, locating these places is potentially important to archaeologists investigating lithic technology, residential mobility, and Aboriginal land use systems. Using silcrete and other geological samples collected from the Dalhousie Springs region, a spectral library was constructed to identify the lithological spectral signature of silcrete and map its distribution in the Dalhousie Springs area. Further digital elevation data are used to identify terrain where natural outcrops of the material may occur. Importantly, this paper shows how remote sensing can be used to discriminate silcrete, which is the raw material from which most of the stone artefacts from this area of central Australia were manufactured. The resultant mapping characterizes its distribution and abundance, which can be used to infer where people may have positioned their encampments and may suggest the most likely landscape context for lithic workshops and quarry sites.

The third research question asks, "How can remote sensing enhance our understanding of Aboriginal ecology and land use in the Australian arid zone?" This chapter revisits prominent ethnographic and archaeological models of arid land use, as proposed by Gould (1977), Veth (1989, 1993), Hiscock (1994, 2008), Hiscock and Wallis (2005), Smith (2013), and Thorley (2001). It uses multiple remote sensing data sources and incorporates suppositions from earlier ecological models to

critically assess habitat suitability in the Western Desert of Australia. Three remote sensing products are used to investigate these models, examining the relationship between surface water distribution, vegetation greenness, and terrain ruggedness. Together, this geospatial information is used to model foraging habitat suitability based on the best environmental conditions observed between 1987 and 2013. Using variables such as maximum vegetation greenness, proximity to water and terrain ruggedness, a new ecological model is presented that evaluates the foraging habitat suitability of the greater Western Desert region. The findings and implications of this work are contextualized with our understanding of earlier models of Aboriginal ecology, land use, and foraging behaviours in desert areas.

1.4 SIGNIFICANCE

There are very few studies within the discipline of Australian archaeology that have explicitly used advanced aerial or satellite remote sensing technologies to investigate Aboriginal archaeology. In fact, it is likely that this PhD one of the first Australian efforts to pointedly use remote sensing methods for this purpose; however, the relevance of this research also extends to other countries that have similar hunter-gatherer archaeological records and arid environmental conditions. The Australian archaeological topics I have selected for remote sensing and geospatial approaches are intended to demonstrate an array of problem-solving techniques that are beneficial for Aboriginal archaeology; however, there is no reason that similar remote sensing investigations could not be conducted in arid regions of North and South America, as well as desertic regions of Africa. The publications from this study will be the seminal literature on this topic and have the potential to impact prehistoric archaeological investigations in Australia and worldwide.

This research has potential to impact how future archaeological surveys in remote arid areas are managed and organised. The difficult logistics of remote area fieldwork is biggest problem faced by arid zone archaeologists. It is physically and mentally challenging to conduct fieldwork in remote regions, and often, the financial costs of equipment and supplies make fieldwork prohibitively expensive. Remote sensing can be used to optimise field time and assist archaeologists by targeting areas of high probability for significant archaeological sites. Mining companies and similar exploration businesses which require compliance archaeological fieldwork will undoubtedly see the financial benefit of desktop-based remote sensing work

prior to archaeological surveys. Native title groups and similar Aboriginal organisations will also value the results as they assist Traditional Owners with maintaining connections to country through the identification of culturally important natural resources.

1.5 THESIS OUTLINE

The remaining chapters of this thesis are organised as follows. Chapter 2 offers a brief history on aerial archaeology and remote sensing in Australia. It addresses the first question outlined in this thesis by showing how the discipline of Australian archaeology has largely ignored the investigative potential of remote sensing for more than forty years.

The next three chapters present case studies that explore how remote sensing data can be analysed in various ways to reveal new environmental information and better understand past Aboriginal land use and archaeological site distribution. Chapter 3 shows how satellite-derived digital elevation data was used to make a digital terrain model, offering a more objective means for interpreting which land units stone arrangement sites are more likely to have been constructed. This chapter has been published as: Law, W. B., Slack, M. J., Ostendorf, B., & Lewis, M. M. (2017). Digital Terrain Analysis Reveals New Insights into the Topographic Context of Australian Aboriginal Stone Arrangements. *Archaeological Prospection*, 24(2), 169-179.

Chapter 4 is a case study that demonstrates how airborne hyperspectral imagery can be used to discriminate and map silicified rock sources, showing how spectral analysis can be used to identify localities where potential 'tool-stone' may be procured for artefact manufacture. This chapter has been published as: Law, W. B., Lewis, M. M., Ostendorf, B., & Hiscock, P. (2019) Reflecting on siliceous rocks in central Australia: Using advanced remote sensing to map ancient 'tool-stone' resources. *Geoarchaeology* 35(3), 400-415.

Chapter 5 is the third and final case study presented in this thesis. This chapter shows how multiple remote sensing and geospatial datasets, including archival time-series of imagery, can be combined to model habitat suitability across the Western Desert, testing previous models of human ecology in a detailed way that previous landscape analyses could not. The outcomes of this research allow us to better understand the great range of Aboriginal subsistence and settlement practices and land use behaviours in this vast arid region. This paper is presented as a journal

article for submission to the journal *Science* for peer-review: Law, W.B., Hiscock, P., Ostendorf, B. and Lewis, M.M. (2020) Using satellite imagery to evaluate precontact Aboriginal foraging habitats in the Australian Western Desert.

The findings and implications of these case studies are thoroughly considered in the context of the overarching theme of this thesis—the relevance of advanced remote sensing technologies for our understanding of past Aboriginal land use and site distribution in the Australian arid zone. The thesis concludes with the recognition that environmental remote sensing has much to offer Australian archaeological research, and it seems that the discipline currently rests on the cusp of a technological revolution. I argue that the breadth and scale of remote sensing's contribution will only be hampered by the technological know-how of researchers and their creative use of aerial and satellite imagery to investigate the Aboriginal archaeological record.

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Chapter 2 A Brief History of Aerial Archaeology and Satellite Remote Sensing in Australia

There must be many thousands of prehistoric sites scattered over the huge continent of Australia that would be worthy of aerial archaeological study. If such study is not attempted soon, and attempted on a far larger scale than has been possible for us, then the fragility of many of those sites may mean that Australians will miss a unique opportunity, of world-wide significance, to investigate hunter-gatherer sites from the air.

-Connah and Jones (1983a, p. 23)

2.1 AERIAL ARCHAEOLOGY IN AUSTRALIA: THE EARLY YEARS

More than thirty years ago, Connah and Jones (1983a, p. 3) observed that “There is nothing new about the *idea* of taking archaeological air photographs in Australia.” Indeed, their observation was true then, and it remains so now. Australian archaeologists have long been aware of the value of aerial imagery for archaeological research, and from the earliest days of this discipline, researchers looked overseas to see how their international colleagues were utilising aerial imaging tools. Connah (1978, p. 99) was acutely aware of the potential for aerial imaging in archaeology, stating, “Archaeological aerial photography emphasizes the usefulness of studying the totality of human influences that have affected the landscapes that we see.” Connah’s research looked heavily towards British applications of aerial imaging (Connah, 1978), and he produced a series of papers (Connah & Jones, 1983a, 1983b) to outline and promote aerial archaeology in Australia, with a particular emphasis on Aboriginal archaeological applications.

The problem for Australian archaeology is, as Connah and Jones (1983a, p. 2) point out, “Most aerial archaeology has concerned itself with the sites of agricultural or urban societies.” Even today, when researching the worldwide application of airborne and satellite imagery for archaeology, most published examples focus on distinguishing crop/soil marks and architectural features. In Australia, it seems that there is a generally accepted notion that aerial archaeology for the investigation of the ancient Aboriginal past is unproductive, has limited application, or it is too expensive. Connah and Jones (1983a) perceived this general attitude themselves stating, “the general lack of interest in aerial archaeology in Australia results principally from doubt about its relevance, in particular its relevance to the archaeology of hunter-gatherers.”

It is not surprising that this perception existed three decades ago. Aerial archaeology in the era of Connah and Jones' research consisted of hiring an aircraft and using film-format cameras to capture imagery from the window seat. The archaeologist-photographer often produced oblique angle aerial photographs of their subject area (e.g., Connah, 1978; Connah & Jones, 1983b; Gould, 1987; Webster, 1964), which resulted in images overlooking their area of interest, but not an end-product that was conducive to georeferencing, mapping or further image manipulation.

In these pioneering days of Australian aerial archaeology, there was a conscious effort to use film to visually differentiate prehistoric archaeological sites from the surrounding environment. Connah and Jones (1983a, pp. 8-14) demonstrated success in using panchromatic black-and-white film to differentiate an array of prehistoric Aboriginal sites, including ceremonial earthworks (i.e., 'bora rings'), stone arrangements, fish-traps, and hearths (Figure 2-1). Connah and Jones' aerial photographs are remotely sensed images, but they are products of an analog age, and the images are restricted to the visible light spectrum, often panchromatic and hence lacking colour or spectral information. The only manner in which these photographs could be manipulated was chemically, during the film negative processing. These black-and-white photos are valuable for overhead observations because they allow the observer to visualise spatial associations, patterns, texture, shadows, brightness, and object sizes. However, from a remote sensing standpoint these historic photos had limited use for enhancing specific terrain or land surface features because they lack colour or spectral information and could not easily be manipulated to highlight or enhance ground surface phenomena.

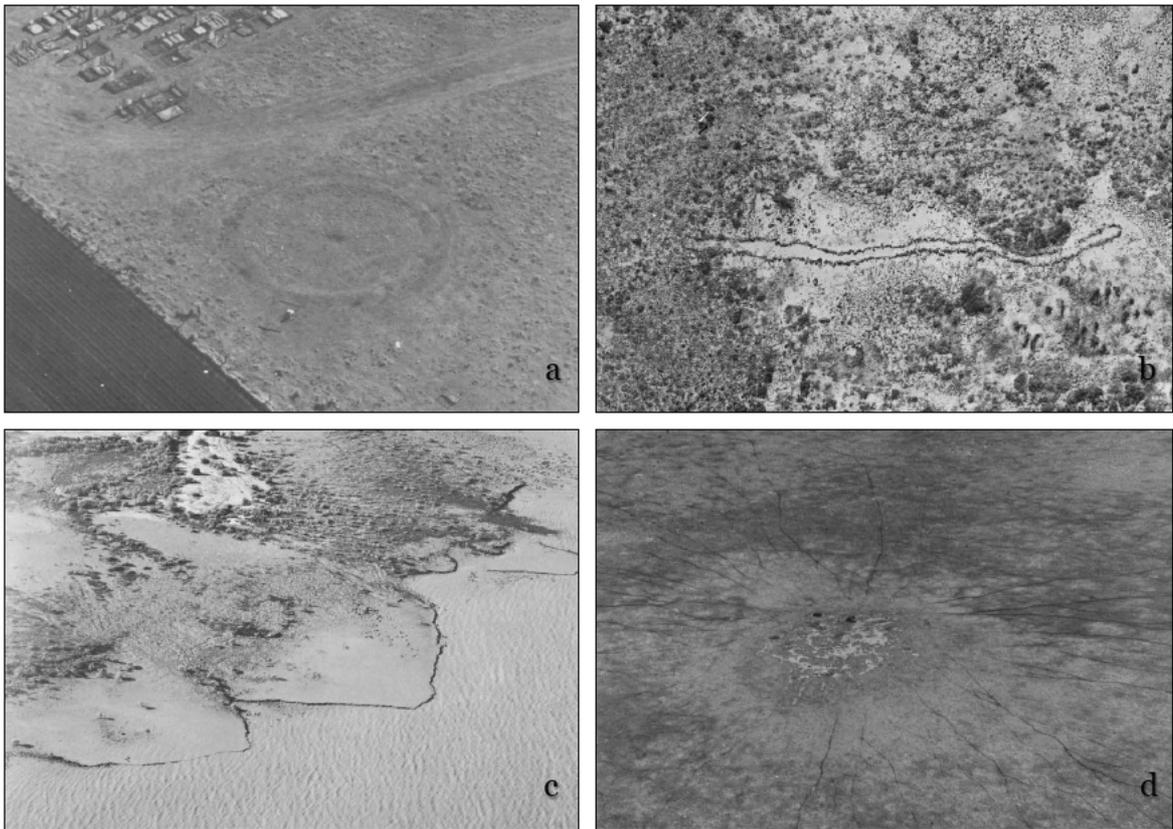


Figure 2-1 Reproduced Connah and Jones (1983a, pp. 8-14) black-and-white aerial photographs of Aboriginal archaeological sites. Images are: (a) Aboriginal earth mound or 'bora ring,' (b) stone arrangement, (c) coastal fish-traps, and (d) soil mark of a prehistoric oven-mound.

Connah and Jones (1983a) admittedly considered their approach low-tech and accomplishable with a reasonable quality 35mm camera. This is because they wanted to emphasise photographic equipment and techniques that were accessible to the greater archaeological community. Connah and Jones (1983a) also recognised that other film types such as colour and infrared could be equally useful for photographing prehistoric archaeological sites. They shied away from using colour film because of the expensive developing costs, but they did point to usefulness of black-and-white infrared photography due to the film's potential to remotely sense and emphasize phenomena outside of the visible light spectrum.

Connah and Jones (1983a) did not have the opportunity to experiment with infrared film, although they cite the collaborative work of McBryde (1962) and Webster (1964) as a successful example of black-and-white aerial infrared photography for prehistoric archaeology. McBryde and Webster's aerial photograph is reproduced in Figure 2-2, and it demonstrates how infrared film visually distinguishes the Mount William stone axe quarry from the surrounding landscape (Webster, 1964, p. 140). Identical imagery was taken with black-and-white film, and the quarry could not be differentiated from the neighbouring ground surface.

Although this infrared image may seem simplistic by today's standards, it is an important historical record, because it is likely that Webster's infrared photo is the earliest example of airborne remote sensing for Aboriginal archaeology in Australia (Figure 2-2).

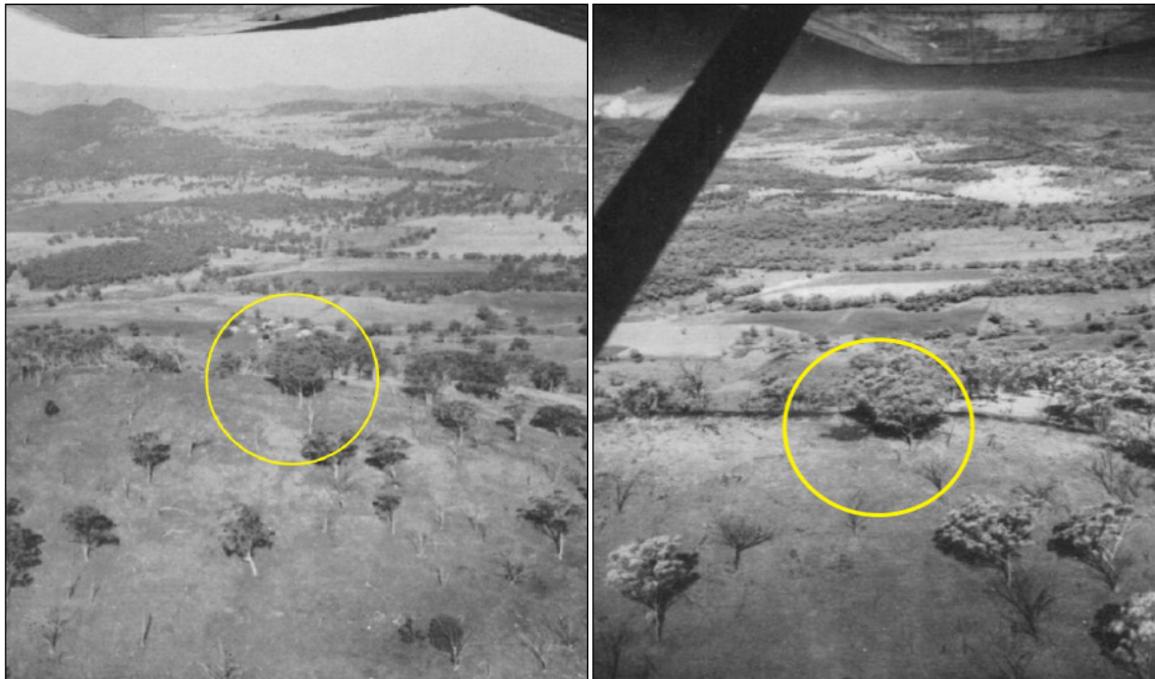


Figure 2-2 The reproduced Webster (1964, p. 140) black-and-white (left) and infrared (right) aerial photographs of the Mount William stone axe quarry (circled). The quarry appears as the amorphous dark area to the left of the large tree in the infrared image (right).

McBryde and Webster's infrared photography was considered innovative in the 1960s, with Mulvaney (1964, p. 429) asserting that "They provided a new perspective for the investigation of aboriginal [sic] stone quarries in N.S.W." Although McBryde (1962) and Webster's (1964) work did not start a revolution in archaeological infrared photography, the Mount William quarry imagery led to an increased awareness that Aboriginal archaeological sites could transform the natural condition of the surrounding environment, and these changes could be remotely sensed. This realisation led some academics to speculate how aerial imagery could be used to sense ancient Aboriginal features preserved in the modern landscape.

Referencing the work of Mulvaney (1964, p. 429), Connah and Jones (1983a, pp. 3-4) cite McPherson's (1884) late nineteenth century observations of Aboriginal hearths preserved in the plains surrounding Meredith, Victoria. While travelling on the Geelong-Ballarat railway, McPherson (1884, p. 49) observed that during times of drought, "black patches" of Aboriginal "oven-mounds" could be "distinguishable

from the bare surface of the soil.” In wetter times, McPherson (1884, p. 49) further noted that, “crops grew green and tall on fertile ashy mounds,” and,

The powdery black ashes of the primitive hearths and cooking-ovens of the aborigines [sic] are distinguishable from the blackest soil and can be traced on the ploughed fields long after the subverting agency of the ploughshare has been at work.”

McPherson’s account provides the modern remote sensing researcher pause for considering if Aboriginal phenomena can be sensed with modern technology. Although these early researchers were considering McPherson’s observations in the context of aerial photography, his account is equally inspiring for the application of aerial remote sensing.

In the period immediately preceding Connah and Jones’ (1983a, 1983b) important synthesis of Australian aerial archaeology, a number of extensive studies demonstrating the usefulness of aerial remote sensing to prehistoric archaeology appeared in the North American literature (Aikens et al., 1980; Avery & Lyons, 1981; Ebert & Lyons, 1980; Lyons et al., 1977; Lyons & Hitchcock, 1977). These early studies emphasised the use of aerial remote sensing as a non-destructive method for investigating and identifying Native American architectural features and prehistoric agricultural phenomena in arid regions of the American southwest. Australian archaeologists were somewhat aware of these studies, as evidenced through Connah and Jones (1983a) citing the New Mexico work of Ebert and Lyons (1980). Therefore, there was an awareness of the inferred usefulness of remote sensing for arid contexts, at least amongst some Australian researchers. Despite the plethora of remote sensing work that was appearing overseas, virtually no archaeological research into the various applications of aerial remote sensing occurred in Australia during the late 1980s or 1990s.

In reviewing the literature from this period, there seems to be only one substantial study on the archaeological applications of remote sensing in Australia. The study was completed by Kearns (1987), an Honours student at the University of Queensland. Kearns’ thesis entitled, “A Preliminary Investigation into the Possible Uses of Remote Sensing in Australian Archaeology,” consisted of a background literature review and a summary of the kinds of aerial or satellite remote sensing data that are useful to Australian archaeologists. Overall, Kearns’ research is thoughtful and well presented, but regrettably his work has been overlooked and

unknown to most archaeologists because it was never published outside his academic department.

Kearns clearly wanted to use remote sensing software to illustrate the usefulness of digitally manipulated aerial imagery in an Australian archaeological context; however, due to financial constraints and imagery accessibility, he was not able to acquire the software or digital imagery. Instead, he relied upon the visual interpretation of aerial photos, using a magnifying device and mirror stereoscope to prospect for archaeological sites. At the time, the visual interpretation of imagery was still widely used because it was considered to be the least expensive and most accessible investigative method for researchers (Kearns, 1987, p. 46). Although, Kearns did not use digital data, his remote sensing review demonstrated a well-read description of computerised digital image enhancement and multispectral statistical techniques, including supervised and unsupervised classification of digital imagery.

Kearns' investigation was thorough in explaining the spatial resolution and spectral limitations of various aerial and satellite imagery products. In some instances, he was able to view photos of early Landsat 3 and 4 satellite imagery, but he concluded that due to the coarse spatial resolution of Landsat imagery, the product would only be useful to archaeologists for "regional analysis where large areas have to be examined and stratified and/or sampled on the basis of environmental variables" (Kearns, 1987, p. 54). For the most part, Kearns used 1:25,000 and 1:12,000 scale black-and-white government aerial photography to identify known archaeological features such as Aboriginal fish traps along the Queensland coast. He also demonstrated the usefulness of time series of imagery to demonstrate the clearing and regrowth of vegetation, discussing the implications of land clearance on Aboriginal sites and its usefulness as a management tool for archaeologists.

Although Kearns' (1987) research was not effective in bringing Australian archaeology into the digital era of remote sensing, it did attempt to increase an awareness of the potential for aerial and satellite remote sensing to become a valuable management and fieldwork planning tool for archaeologists. Kearns points to the relevance of remote sensing as a tool for survey planning, site discovery, and site monitoring. Recognising the same problems as Connah and Jones (1983a), Kearns (1987, p. 5) also observed that aerial and satellite remote sensing "has received little attention for such purposes from researchers in Australia." Kearns

(1987, p. 97) was admittedly “puzzled” by the overall disinterest in remote sensing amongst the archaeological community, stating,

Given the vast area of Australia and the relatively small size of the archaeology community in this country one would have thought the data gathering, analysis and storage potential of remote sensing would have sparked off more interest than it has. There is a vast body of literature and actual data which is seemingly ignored and/or unknown by the majority of Australian archaeologists when they casually dismiss remote sensing as being irrelevant and/or impracticable. Overseas and Australian work...clearly indicates that there is some potential for remote sensing in Australian archaeology.

In conclusion, Kearns (1987, pp. 92-94) observed several technological trends that could potentially raise the profile of remote sensing in the future. The first trend is continued improvement of desktop analytical software and access to digital data. Kearns argued that in the future, this trend would allow archaeologists to conduct their own analysis without relying on outside expertise or data.

The second trend which Kearns (1987, p. 94) believed would endear archaeologists to remote sensing is improved spatial and spectral resolution of aerial and satellite imagery. Kearns’ research demonstrated that 1:25,000 or 1:12,000 aerial imagery was more useful in identifying archaeological phenomena than Landsat images, but satellite imagery is better suited for regional environmental patterns due its broader geographic coverage, coarser spatial resolution and multispectral properties. His work predicted that future refinements of satellite spatial and spectral resolution would likely improve its usefulness for archaeological researchers.

The final trend that Kearns (1987, p. 94) argued would increase interest in remote sensing technology would be “personalised” data collection via “a small highly controllable, stable and inexpensive aerial platform would allow archaeologist to carry out their own aerial survey.” In a sense, Kearns was referring to drones, which at the time of his research were model aircraft, lacking the technical, payload and control capabilities that drone platforms have evolved into today.

In the decades following his assessment, there has been continuous improvement in nearly every aspect of the trends Kearns observed. The ideas presented in his thesis are well-researched, and his description of remote sensing analysis is sound for its context. The main component missing from Kearns’ remote

sensing work is digital imagery and examples of how the digital data can be extracted and statistically manipulated using computer software. His research was effectively an analog study of remote sensing, placed in the context of pre-internet world. In many ways, Kearns' research was ahead of its time, so it is interesting to review how remote sensing has been applied to Australian archaeology in the 30 years since his thesis.

By the late 1990s/early 2000s there were signs that Australian research was moving into an era that was becoming more accepting and interested in aerial imagery. Schlitz (2004) published a review article on how low level aerial photographic methods and recording platforms with drones, kites, balloons, and telescoping poles were potentially revolutionising archaeology. His review included a brief discussion of digital camera types that may be mounted onto various platforms; but does not explicitly discuss remote sensing or sensor types. Like the researchers before him, Schlitz (2004, p. 57) recognises that there is lack of interest in aerial photography amongst the general archaeological community, concluding that "practitioners of low-level aerial archaeology in Australia are rare." Nevertheless, Schlitz was optimistic about the future of aerial archaeology, implying that the emergence of new low-cost platforms will elevate the importance of aerial photography for future Australian projects.

2.2 AERIAL AND SATELLITE REMOTE SENSING IN AUSTRALIA: THE MODERN ERA

Much has changed since the earlier 'analog' period of aerial archaeology in Australia. Since the 1990s, and especially in past decade, a wealth of digital remote sensing imagery and derived products has amassed in archives and repositories, and much of it is easily accessed through a variety of government-sponsored or open access online portals. With improved data accessibility and a greater familiarity with GIS software, Australian archaeological researchers are beginning to notice the usefulness of environmental remote sensing, and a couple of well-received international journal articles have raised the profile of using Earth observation data to model and interpret the Australian archaeological record (Bird et al., 2016; Bliege Bird et al., 2008). However, in comparison to other natural science fields, applied examples of advanced remote sensing for Australian archaeology are generally limited to historic studies and emphasise documenting and detecting colonial buildings or site structures (Schlitz 2004; Tuffin et al., 2020). Prehistoric

applications are scant, but they are certainly on the rise and on the forefront of much contemporary research, as discussed below.

The following subsections explore the nature of this increase by way of peer-reviewed publications and data availability. The first subsection discusses how aerial and satellite remote sensing is currently being applied to Aboriginal archaeology, highlighting particular case studies where advanced remote sensing is critical to the research findings. Given that so few modern Australian archaeological studies have utilised remote sensing products or datasets, it is important to recognise which areas of the discipline are utilising advanced remote sensing data and how the information is being integrated with contemporary studies.

The second subsection provides a tabled list and brief description of a selection of remote sensing products that are useful for investigating the Aboriginal archaeological record. It is presented here to provide a sample of the range of information that is available with open access to researchers. Moreover, many of these image products are used in the case studies of this thesis. Thus, the intent of this second subsection is to summarise the data sources used in my research.

2.2.1 Advanced Remote Sensing for Australian Archaeology

In recent times, there have been a number of international books, edited volumes, and special journal publications demonstrating the beneficial aspects of remote sensing to a diverse number of prehistoric archaeological projects around the world (Lasaponara & Masini, 2011, 2012; Parcak, 2009; Wiseman & El-Baz, 2007). Disappointingly, Australian archaeological themes do not feature in any of these major studies, and aside from the original research output related to this thesis (e.g., Law et al., 2020; Law et al., 2017), there are few peer-reviewed articles where environmental remote sensing is used within the framework of contemporary Aboriginal archaeological studies. However, whenever remote sensing data are integrated with an Aboriginal archaeological topic, the remote sensing aspect is always featured prominently (e.g., Bird et al., 2016; Bliege Bird et al., 2008; Kreij et al., 2018). There are few contemporary articles in this area, highlighting how infrequently archaeology and remote sensing studies are integrated in Australia. Yet there is anecdotal evidence that discipline is changing, as a substantial number of archaeological remote sensing papers has been presented at the annual Australian Archaeological Association Conference over the past five years (Kreij, 2019; Kreij et

al., 2015; Kreij et al., 2016; Law et al., 2018; Law et al., 2017; Law et al., 2015; Nagel, 2019; Nagel et al., 2017).

In the late 1990s and early 2000s, researchers began using Earth observation data to explore question related to Aboriginal fire ecology. Researchers utilised multispectral satellite imagery to investigate the landscape burning practices of present-day Aboriginal peoples (Bliege Bird et al., 2008; Bowman, 1998). In these examples, Landsat imagery was analysed to accurately map areas impacted by cultural burning practices, revealing recent landscape fire histories. These studies focused heavily on the physical evidence left on the landscape from traditional cultural burning practices, demonstrating that the contemporary legacy of Aboriginal land management practices also has implications for interpreting the archaeological record.

For instance, Bliege Bird et al. (2008) revisited the ethnoarchaeological observations of Jones' (1969) "fire stick farming hypothesis," a prominent archaeological model that has been critiqued for some time amongst Australian archaeological scholars. Jones' hypothesis argues that Aboriginal people have used fire for hunting, foraging, land clearance and plant rejuvenation purposes for thousands of years, and perhaps anthropogenic burning led to the extinction of Pleistocene megafauna. Bliege Bird et al. (2008) used Landsat-5 imagery to compare the patterns of fire scars resulting from anthropogenic and lightning fire regimes in the Western Desert. They conclude that the anthropogenic burning of grasslands does not extend uniformly across the landscape, occurring in smaller patches than lightning-induced burns. Where anthropogenic burning does occur, the resulting mosaic patterning of burned vegetation limits the area potentially burned by natural lightning fires. Thus, in other words, if there is a dense mosaic of anthropogenically burned patches across the landscape, then the potential for lightning-started fires to burn large areas of the landscape is diminished. The vegetation gaps created by the anthropogenic fire mosaic effectively serve as a fuel break, confining and limiting the area burnt by uncontrolled lightning fire regimes. Based on this pattern, Bliege Bird et al. (2008, p. 14800) conclude that if archaeologists are correct that late-Pleistocene/early-Holocene Aboriginal group sizes were smaller and more mobile than the Aboriginal populations of the past 1,500 years, then it is unlikely that ancient Aboriginal populations burned enough of the arid zone landscape to limit the larger and more widespread burning effects of lightning fire regimes. Thus, it

seems unlikely that anthropogenic burning led to the demise of Pleistocene megafauna.

Interestingly, the setting of the Bliege Bird et al. (2008) study is in the Australian arid zone, which infers that the research team recognised this desertic region of the continent as being well-suited for remote sensing applications. The limited ground cover in Australian deserts provides clear Earth surface observations, allowing for optical sensors to more clearly sense ground surface phenomena and natural resources. Given that understanding the natural resources of arid lands is important for investigating the archaeological record, it is not surprising that a research theme tied to understanding resource distribution has emerged as an important area for archaeological remote sensing in Australia (e.g., Bird et al., 2016; Law et al., 2020).

The natural resource theme is exemplified in a recent study published by Bird et al. (2016). Their research is based on Water Observations from Space (WOfS), a product derived from the 26 year Landsat-5 satellite image collection (Geoscience Australia, 2015). Using this datacube of information, Bird et al. (2016) hypothesise that the early Aboriginal colonisation of Australia was tied to the connectedness and distribution of inland continental water. This was the first major publication to directly incorporate analysis of time-series satellite imagery into a deep-time model of the Australian archaeological record. The research is important because it offers insights into the early peopling of the continent, allowing for early colonisation hypotheses to be explored and refined. Using WOfS data to model the pre-30,000 year dispersal of peoples throughout the arid and semi-arid zone, Bird et al. (2016) revealed a series of hypothetical colonisation routes from northern Australia through the eastern semi-arid and arid zone and into southeastern and central Australia. This eastern colonisation route has not been posited before, and unlike preceding colonisation hypotheses, Bird et al. (2016) argue that the model is testable and supported by remote sensing metrics. In short, the Bird et al. (2016) study is innovative in its scope, and it is a good example for how remote sensing is poised to impact future archaeological research.

The Bliege Bird et al. (2008) and Bird et al. (2016) studies are the most archaeologically relevant examples of remote sensing techniques used in the context of this PhD research; however, it is important to note that in recent years there has been a clear trend towards the acquisition of customised, high resolution remote sensing imagery of Aboriginal archaeological sites (Kreij, 2019; Kreij et al., 2015;

Kreij et al., 2018; Kreij et al., 2016; Nagel et al., 2017). Unmanned aerial vehicles (UAV), or drones, are the principal driver behind the acquisition of high resolution, bespoke imagery of archaeological places. Detailed multispectral data, digital elevation data and photogrammetric imagery can be acquired from sensors attached to UAVs, resulting in customised imagery from areas of interest. These customised image datasets are already providing new insights into how particular Aboriginal constructions like fish traps may have functioned in the past (Kreij et al., 2015; Kreij et al., 2018; Kreij et al., 2016; Nagel et al., 2017). As drone technologies continue to improve and payload capacities increase to accommodate new sensors, it is highly likely that drone-acquired remote sensing data will become a huge area of growth and perhaps one day dominate archaeological remote sensing studies in Australia. However, for the time being, this thesis focuses on data acquired through satellite and aircraft platforms but acknowledges the promise and potential of remote sensing datasets acquired through UAV-related technologies.

Based on the findings of this literature review, there appear to be few studies that have utilised remote sensing data to better understand the Aboriginal archaeological record. The dearth of research in this area illustrates that Australian researchers have yet to fully appreciate the relevance of remote sensing to Aboriginal archaeology, and it seems fair to surmise that the archaeological community has largely not embraced aerial and satellite remote sensing in the years since Kearns' (1987) initial assessment, despite the clear contribution that remote sensing has made to archaeological investigations and discoveries elsewhere in the world. This literature review is largely in agreement with Kearns' findings, as it is apparent that there has been a long-term knowledge gap in the field of remote sensing for Australian archaeology.

2.2.2 Sources of Aerial and Satellite Imagery

In other parts of the world, there has been a substantial increase in the use of remote sensing data for archaeological research. European researchers Lasaponara and Masini (2011, p. 1995) attest that there has been the strong increase in the use of aerial and satellite imagery for archaeological investigations over the past twenty years. This is largely due to:

- 1) the improvement of spectral and spatial resolution of satellite sensors;
- 2) the availability of user-friendly software and routines for data processing and analysis;

- 3) the interests of archaeologists to study the dynamics of human frequentation in relation to environmental changes.

Lasaponara and Masini (2011, p. 1995) further stress that archaeologists are more aware of the project management benefits of remote sensing, including reducing project costs and improving project outcomes. Many researchers now use remote sensing imagery in the early planning stages of archaeological projects, helping to target excavation or survey areas and reduce research costs and risks. Remote sensing image products can further be used for landscape analysis and monitoring in pre and post-fieldwork periods, thereby addressing future site conservation and preservation concerns.

There is no reason that Australian archaeologists cannot also benefit from the technological improvements and data accessibility recognised by Lasaponara and Masini (2011). In agreement with their assessment, Table 2-1 is presented for the purpose of introducing Australian archaeological researchers to a range of remote sensing products that are available to support their research, especially in regards to ecologically themed studies of human-environment interactions. It is important to stress that the list of aerial and satellite image products in Table 2-1 is not comprehensive, and for the sake of simplicity, it does not include specialised forms of remote sensing like LiDAR (see Hesse 2010) and Synthetic Aperture Radar (see Chen et al., 2017), which may be useful for studies of structural remains. Instead, Table 2-1 aims to highlight a variety of DEM, multispectral and hyperspectral products that are easily accessed by researchers. The table also summarises the spatial and spectral characteristics of the imagery, to assist with determining which platform and sensor combination may be most appropriate for particular research purposes.

For decades, there have been numerous satellites continuously acquiring imagery of our planet, so it is not surprising that Earth observation datasets are abundant. NASA, the US Geological Survey, Geoscience Australia, the Japan Aerospace Exploration Agency (JAXA), the European Space Agency (ESA) all have large repositories of imagery and related digital products, much of which is available to users through online interfaces (Table 2-1). Additionally, a comprehensive database of non-commercial remote sensing missions, instruments, measurements and datasets has been compiled by the International Committee on Earth Observation Satellites (CEOS 2020), and researchers like Harrison et al. (2016) have published thorough evaluations of satellite products most widely used in Australia.

Table 2-1 A selection of satellite and aerial imagery sources useful to Australian archaeology, including products used in this research (*).

Image Product	Cost	Website	Spatial Resolution & Scene Size	Spectral Resolution	Temporal Resolution	Archaeological Applications
ALOS World 3D*	Free	eorc.jaxa.jp	~30 m pixel 108-x-108 km tiles	Single Band DEM (MAMSL)	2006-2011	JAXA's Advanced Land Observing Satellite (ALOS) Global Digital Surface Model (DSM) was used for topographic, terrain, and hydrology mapping. Geomorphometric algorithms were used to analyse the DSM and classify topographic land units (Chapter 3) and measure the terrain ruggedness (Chapter 5). Applications include exploring site types by landforms and modelling terrain classes. Compared to other DEM products, the advantage of the ALOS is that it has a low level of 'pixel noise' and the DSM is applicable in arid Australia due to a lack of dense tree canopies obscuring ground elevation measurements.
ASTER	Free	ga.gov.au glovis.usgs.gov landcover.org	15 to 90 m pixel 60-x-60 km tiles	14 Multispectral Bands: VNIR (0.52-0.60µm; 0.63-0.69µm; 0.76-0.86µm) SWIR (1.6-1.7µm; 2.145-2.185µm; 2.185-2.225µm; 2.235-2.285 µm; 2.295-2.365µm; 2.360-2.430 µm) TIR (8.125-8.475µm; 8.475-8.825µm; 8.925-9.275µm; 10.25-10.95µm; 10.95-11.65µm)	16-day repeat 1999 to present	The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a Japanese imaging instrument on board USA's TERRA satellite. The medium resolution ASTER multispectral satellite is the world's first 'geoscience-tuned' satellite and may be used for regional natural resource mapping and discriminating water, mineral, soil, and vegetation communities.
ASTER Geoscience Map of Australia*	Free	doi.org/10.4225/08/51400D6F7B335	15 to 90 m pixel 60-x-60 km tiles	Variable Archived collection of CSIRO-analysed ASTER imagery, including numerous single band mineral indices and false colour imagery of Earth's surface.	Product is a mosaic of various imagery acquired prior to April 2008 (SWIR bands become non-operational after this date)	This ASTER satellite-derived product was created by CSIRO (Cudahy et al. 2012) to reveal continental scale mineralogy for Australia. It is a continental-scale mosaicked collection of CSIRO analysed digital imagery of the Earth's surface mineralogy, including: Iron oxides; clays; carbonates; silica; quartz; muscovite and chlorite. ASTER "Silica Index" mineral maps were used in Chapter 4 to reveal siliceous rock lithology and potential raw material resources.
ASTER GDEM	Free	reverb.echo.nasa.gov	30 to 90 m pixel 108-x-108 km tiles	Single Band DEM (MAMSL)	Acquired 2009	Medium resolution DEM satellite imagery for topographic, terrain, and hydrology mapping. Can be used for geomorphometry and land surface classification. Applications include exploring site types by landforms and modelling terrain.
Google Earth	Free	earth.google.com	Variable ~0.1 to 30 m pixel Ad hoc tile size	True Colour (RGB)	Variable, as acquired	High to medium resolution satellite and aerial imagery from various vendors. Useful for rapid national and regional mapping, discriminating visible surface features (e.g., drainages, bare soils, and roads) and providing an overview of archaeological site locations. Can possibly discern some Aboriginal archaeological features (e.g. mounds, hearths, cairns, stone arrangements or fish traps).

Abbreviations: DEM = Digital Elevation Model; MAMSL = Meters Above Mean Sea Level; VNIR = Visible and Near Infrared; SWIR = Shortwave Infrared; TIR = Thermal Infrared

Table 2-1 (continued) A selection of satellite and aerial imagery sources useful to Australian archaeology, including products used in this research (*).

Image Product	Cost	Website	Spatial Resolution & Scene Size	Spectral Resolution	Temporal Resolution	Archaeological Applications
Google Earth	Free	earth.google.com	Variable ~0.1 to 30 m pixel Ad hoc tile size	True Colour (RGB)	Variable, as acquired	High to medium resolution satellite and aerial imagery from various vendors. Useful for rapid national and regional mapping, discriminating visible surface features (e.g., drainages, bare soils, and roads) and providing an overview of archaeological site locations. Can possibly discern some Aboriginal archaeological features (e.g., mounds, hearths, cairns, stone arrangements or fish traps).
HyMap*	Commercial-project specific cost \$\$\$\$\$ to \$\$\$\$\$ per scene	hyvista.com	2 to 10 m pixel Variable scene size, 2.3-x-2.3 km or 4.6-x-4.6 km arc common	128 Hyperspectral Bands VNIR through SWIR: 0.45-2.50 µm	Custom order	High spatial and spectral resolution hyperspectral imagery from airborne sensor useful for regional and local mapping of water, mineral, soil and vegetation resources. HyMap was used in Chapter 4 to map silcrete 'tool stone' by identifying hydrated silica mineralisation. Also useful for derivation of vegetation indices (e.g., NDVI & EVI).
Landsat Satellites: Landsat-5 and Landsat-8	Free	landsatlook.usgs.gov ga.gov.au glovis.usgs.gov landcover.org sentinel-hub.com	15 to 60 m pixel 185-x-185 km tiles	Landsat-5 7 Multispectral Bands: VNIR (0.45-0.52 µm; 0.52-0.60 µm; 0.63-0.69 µm; 0.77-0.90 µm) SWIR (1.55-1.75 µm; 2.09-2.35 µm) TIR (10.40-12.50 µm) Landsat-8 1 Panchromatic Band: 0.50-0.68 µm 10 Multispectral Bands: VNIR (0.43-0.45 µm; 0.45-0.51 µm; 0.53-0.59 µm; 0.64-0.67 µm; 0.85-0.88 µm) SWIR (1.57-1.65 µm; 2.11-2.29 µm) TIR (10.60-11.19 µm; 11.5-12.51 µm) Cirrus (1.36-1.38 µm)	16-day repeat Landsat-5: 1984 to 2013 Landsat-8: 2013-present	Although since 1972 there have technically been eight Landsat missions launched (Landsat-1 through Landsat-8), it is the Landsat-5 and Landsat-8 satellites that are considered the most meaningful for archaeological applications. Both Landsat-5 and Landsat-8 offer medium resolution multispectral imagery capable of regional mapping of water, mineral, soil, and vegetation resources. Capable of discriminating vegetation communities and calculating vegetation greenness indices (e.g., NDVI & EVI) and burnt area indices (normalised burned ratio). The Landsat-8 product also offers a high resolution panchromatic band, which can be used for image sharpening.
Landsat-5 TM Tier 1, 8-Day NDVI Composite*	Free	earthengine.google.com	~30 m pixels 185-x-185 km tiles	Single Band NDVI (-1 to 1)	16-day NDVI composite images from 1984-2012	This USGS-produced (2012) Normalised Difference Vegetation Index (NDVI) composite data is stored as a datacube in Google Earth Engine (GEE), a cloud-based archive and image analysis hub. Time-series imagery can be readily analysed on this centralised cloud-based server, freeing local machine memory. This datacube of NDVI composite values was used to calculate 95 percentile NDVI values used in Chapter 5. The GEE interface requires coding capability, but many tutorials are available online.

Abbreviations: DEM = Digital Elevation Model; MAMSL = Meters Above Mean Sea Level; VNIR = Visible and Near Infrared; SWIR = Shortwave Infrared; TIR = Thermal Infrared

Table 2-1 (continued) A selection of satellite and aerial imagery sources useful to Australian archaeology, including products used in this research (*).

Image Product	Cost	Website	Spatial Resolution & Scene Size	Spectral Resolution	Temporal Resolution	Archaeological Applications
Sentinel-2A	Free	sentinel-hub.com	10 to 60 m pixel 100-x-100 km tiles	13 Multispectral Bands VNIR: 0.421-0.457 µm; 0.439-0.535 µm; 0.537-0.582 µm; 0.646-0.685 µm; 0.694-0.714 µm; 0.731-0.749 µm; 0.768-0.796 µm; 0.767-0.908 µm; 0.848-0.881 µm; SWIR (1.539-1.681µm; 2.072-2.312µm) Vapour (0.931-0.958 µm) Cirrus (1.338-1.414 µm)	5-day repeat 2015-present	High to moderate spatial resolution and multispectral capabilities. Moderately good at discriminating soils and general geological units, but greatest strength of Sentinel 2A is discriminating water feature and vegetation greenness indices (e.g., NDVI & EVI). Also useful for mapping burnt areas (normalise burned ratio). Easily visualised and processed through the cloud computing available via the Earth Observation browser on sentinel-hub.com.
SRM	Free	ga.gov.au	30 to 90 m pixel 108-x-108 km tiles	Single Band DEM (MAMSL)	Acquired 2000	NASA's Space Shuttle Radar Topographic Mission DEM imagery with global coverage. Useful for topographic, terrain, and hydrology mapping. Can be used for geomorphometry and land surface classification. Applications include exploring site types by landforms and modelling terrain classes.
Quickbird	~\$17,50m ² (USD)	digitalglobe.com	0.6 to 3.2 m pixel 16.5-x-16.5 km tiles	1 Panchromatic Band: 0.45-0.90µm 4 Multispectral Bands: Blue: 0.45-0.52 µm Green: 0.52-0.60 µm Red: 0.63-0.69 µm NIR: 0.76-0.90 µm	1 to 3.5 day repeat 2001 to 2015	High resolution panchromatic and multispectral satellite imagery. Capable of regional and local mapping of water, mineral, soil, and vegetation resources. Vegetation can be discerned at a community or species level, however limited multispectral bands. Can possibly discern some Aboriginal archaeological features (e.g. mounds, hearths, cairns, or fish traps).
WoFS*	Free	ga.gov.au	~30 m pixel 185-x-185 km tiles	Single Band (% observations)	Based on Landsat-5 TM 1987 to 2013	Summary of surface water observations across the entire Australian continent. Used in Chapter 5 for locating and mapping maximum known surface water resources where inundation has been observed in >5% of observations.

Abbreviations: DEM = Digital Elevation Model; MAMSL = Meters Above Mean Sea Level; VNIR = Visible and Near Infrared; SWIR = Shortwave Infrared; TIR = Thermal Infrared

The products listed in Table 2-1 represent some of these datasets, and they were selected to emphasise free or low-cost imagery. However, the table also includes some high spatial and spectral resolution aerial image products that are available commercially and which may be more appropriate for some projects. Table 2-1 also summarises the aerial and satellite remote sensing products used in my PhD research and identifies where the original data sources may be accessed. It briefly describes how each data product was analysed to create useful environmental and archaeological information, and it highlights a wide range of applications for the datasets.

Most of the images and satellite-derived products used in this thesis have medium resolution, with pixel sizes of at least 30 x 30m, and nearly all were accessed through online websites. These medium resolution products offer a good entry point for Australian archaeologists because they are free and their coverage spans the continent. Moreover, all of the products in Table 2-1 are available in georeferenced, analysis-ready form and can be visualised and manipulated in most GIS and remote sensing software packages.

A possible shortcoming of free satellite imagery is that it typically has low (>60m) or medium spatial resolution (~30m), and may not serve some research purposes. A small component of my research benefitted from free access to specialised high spatial and spectral resolution imagery (e.g., HyMap airborne hyperspectral image mosaic) that had been acquired for prior projects and was made available through a license agreement. High resolution imagery of this nature can be expensive, and the associated costs may be prohibitive for some researchers. However, if high spatial resolution (<10m) or very high spatial resolution (<2.5m) products are required, they can be obtained from commercial suppliers. Custom imagery with higher spectral resolutions (i.e., hyperspectral) can also be ordered from specialist providers, and increasingly, with the assistance of drone technology, research teams are acquiring ad hoc imagery for specific sites.

2.3 SUMMARY

Both in historic and contemporary Australian archaeological studies, it is uncommon for remote sensing data to be utilised and it rarely sits at the forefront of research. In the first few decades of Australian archaeology, remote sensing was viewed as being irrelevant to investigating the Aboriginal past because hunter-gatherer societies did not construct large architectural structures or significantly

modify landscapes (e.g., agriculture) in a manner that could be sensed with aerial or satellite imagery. However, in more recent times, the main obstacles have been data and information costs, accessibility and technical training opportunities.

Some recently published and well-received international publications suggest that Australian archaeologists are slowly becoming aware of the usefulness of environmental information derived from remote sensing data, and such information is increasingly accessible from leading scientific institutions around the globe. These advances are promising for investigation of the ancient Aboriginal archaeological record, but there is still a significant knowledge gap pertaining to the application of remote sensing technologies for Australian archaeology. In this regard, the case studies presented in the next three chapters contribute to narrowing this gap, by exploring how remote sensing can assist with the investigation and modelling of past Aboriginal land use, resource use and hunter-gatherer ecological dynamics in the Australian arid zone.

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Contribution to the Paper	With M.J.S., W.B.L. conceived the research project and supervised fieldwork; W.B.L. conducted the background research, designed the methodology, and performed the spatial analysis; W.B.L. wrote the paper and prepared the figures and tables.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	25/03/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

- i. the candidate's stated contribution to the publication is accurate (as detailed above);
- ii. permission is granted for the candidate to include the publication in the thesis; and
- iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Chapter 3 Digital Terrain Analysis Reveals New Insights into the Topographic Context of Australian Aboriginal Stone Arrangements

3.1 ABSTRACT

Satellite-derived surface elevation models are an important resource for landscape archaeological studies. Digital elevation data are useful for classifying land features, characterizing terrain morphology, and discriminating the geomorphic context of archaeological phenomena. This paper shows how remotely sensed elevation data obtained from the Japan Aerospace Exploration Agency's Advanced Land Observing Satellite was integrated with local land system spatial data to digitally classify the topographic slope position of seven broad land classes. The motivation of our research was to employ an objective method that would allow researchers to geomorphometrically discriminate the topographic context of Aboriginal stone arrangements, an important archaeological site type in the Pilbara region of northwest Australia. The resulting digital terrain model demonstrates that stone arrangement sites are strongly correlated with upper topographic land features, a finding that contradicts previous site recordings and fundamentally changes our understanding of where stone arrangement sites are likely to have been constructed. The outcome of this research provides investigators with a stronger foundation for testing hypotheses and developing archaeological models. To some degree, our results also hint at the possible functions of stone arrangements, which have largely remained enigmatic to researchers.

3.2 INTRODUCTION

Documenting and understanding the context of archaeological sites in relation to surrounding terrain features is essential to landscape archaeological studies worldwide (De Reu et al., 2013; De Reu et al., 2011; Turrero et al., 2013). Satellite-derived digital elevation data offer the modern archaeologist a powerful information platform for the analysis and modelling of land surfaces (Hritz, 2014; Keay et al., 2014; Lasaponara & Masini, 2011, 2012; Parcak, 2009; Wiseman & El-Baz, 2007). Remotely sensed digital elevation models (DEM) and digital surface models (DSM) are useful datasets for investigating the distribution of archaeological sites in a broad landscape context, giving researchers the ability to classify and model terrains with greater accuracy and less subjectivity than traditional field methods.

The effectiveness of this approach is exemplified in our research of Aboriginal stone arrangement sites from the Banjima Native Title Claim Area, located in the Pilbara region of northwest Australia (Figure 3-1). Although stone arrangement sites are found throughout Australia, few studies have identified the site densities noted for the inland Pilbara, and in particular, the Packsaddle Valley area of the central Hamersley Plateau (Hook, 1999; Hook & Di Lello, 2010; Hook et al., 2010; Hook et al., 2002; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b) (Figure 3-1). It is unclear if the high frequency of Packsaddle Valley stone arrangement sites is due to ancient cultural behaviours or if it is a product of survey coverage, as much of the area has been intensively surveyed for proposed mining development. Regardless of site numbers, it is well known that stone arrangements are culturally significant to the contemporary Aboriginal groups, and investigators are intrigued by their enigmatic function and curious concentration in the Packsaddle Valley area (Hook, 1999; Hook & Di Lello, 2010; Hook et al., 2010; Hook et al., 2002; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b).

Previous research has shown that there is conflicting information on the topographic context of Packsaddle Valley stone arrangements. Archaeological site records from the Western Australian Department of Aboriginal Affairs (DAA) indicate that Packsaddle Valley stone arrangements most often occupy lower topographic landforms such as stony plains, valley floors, and lower hillslopes (Hook et al., 2010). More recently, investigators have observed that officially registered site details such as the topographic and geomorphological setting are frequently inaccurate and vulnerable to subjective or inconsistent field assessments (Law, 2014a, 2014b). The consequence of erroneous recording is a skewed distributional pattern that suggests stone arrangements more frequently occur in lower topographic land units. New survey data, including site revisits, suggests that stone arrangements are more likely to be constructed on hilltops and hillslopes (Law, 2014b); however, the latest information is based on a limited sample of 26 sites in a localised area and may not be representative of a regional pattern.

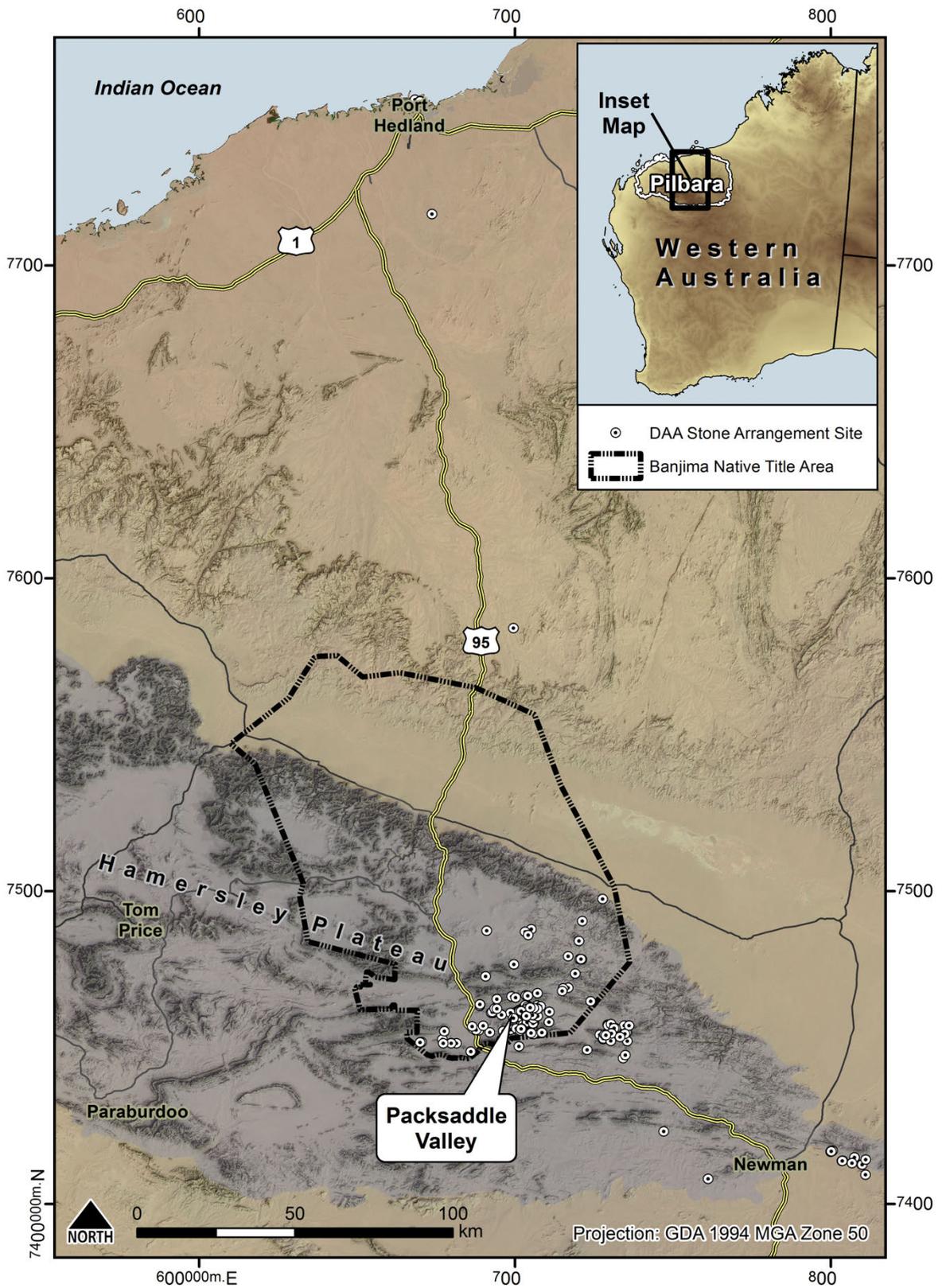


Figure 3-1 Regional overview map with major geographic features, Department of Aboriginal Affairs (DAA) registered stone arrangement sites, cultural areas, and the approximate position of the Packsaddle Valley, Pilbara region of Western Australia.

One of the greatest implications of the conflicting information is that archaeologists, land managers, policy makers, and Aboriginal stakeholders are inadequately guided in their research and conservation decisions. Simply put, if the geomorphic context and topographic distribution of stone arrangements cannot be characterised, then it is difficult to effectively protect sites, manage lands, and conserve areas where unrecorded stone arrangements may exist.

Our research aims to resolve the question of where stone arrangement sites are distributed in the Packsaddle Valley area by using satellite-derived digital elevation models and digital land system data. Although the archaeological subject matter of this study is uniquely Australian, the principles and methods espoused herein are applicable to all researchers interested in using digital elevation data to model archaeological site distribution and terrain features.

3.3 THE PACKSADDLE VALLEY STUDY AREA

3.3.1 Environmental Setting

The Packsaddle Valley is in the Pilbara biogeographic region, an arid rangeland environment receiving an average of 322mm rainfall annually (Bureau of Meteorology, 2016). Rainfall is largely correlated with summer cyclone events, and average rainfall is rarely attained without the contribution of cyclonic activity. The Packsaddle Valley extends along an east-west corridor, dissecting the North Flank and Packsaddle Ranges (Figure 3-2). The study area of 364.4 sq. km is roughly framed by the Great Northern Highway on the west, the Banjima Native Title Claim boundary on the south, and various government land parcel boundaries on the north and east (Figure 3-2).

The Department of Agriculture and Food, Western Australia (DAFWA) has defined and mapped five dominant land systems in the Packsaddle Valley area. For this study, these land systems are broadly divided into upland or lowland classes, based on their topographic relief and land features (Table 3-1 and Figure 3-2). The Newman Land System is the only upland land system, occupying 65.8 percent of the study area. It includes plateaux, ridges, and mountains with relief of up to 450m (Payne, 2004). Prominent land features include exposed ridges, vertical escarpments, and weathered hilltops with skeletal soils. Deep gullies dissect much of the Newman land surface, exposing the layered and sometimes folded bedding of Proterozoic-age banded ironstone (Trendall et al., 1998).

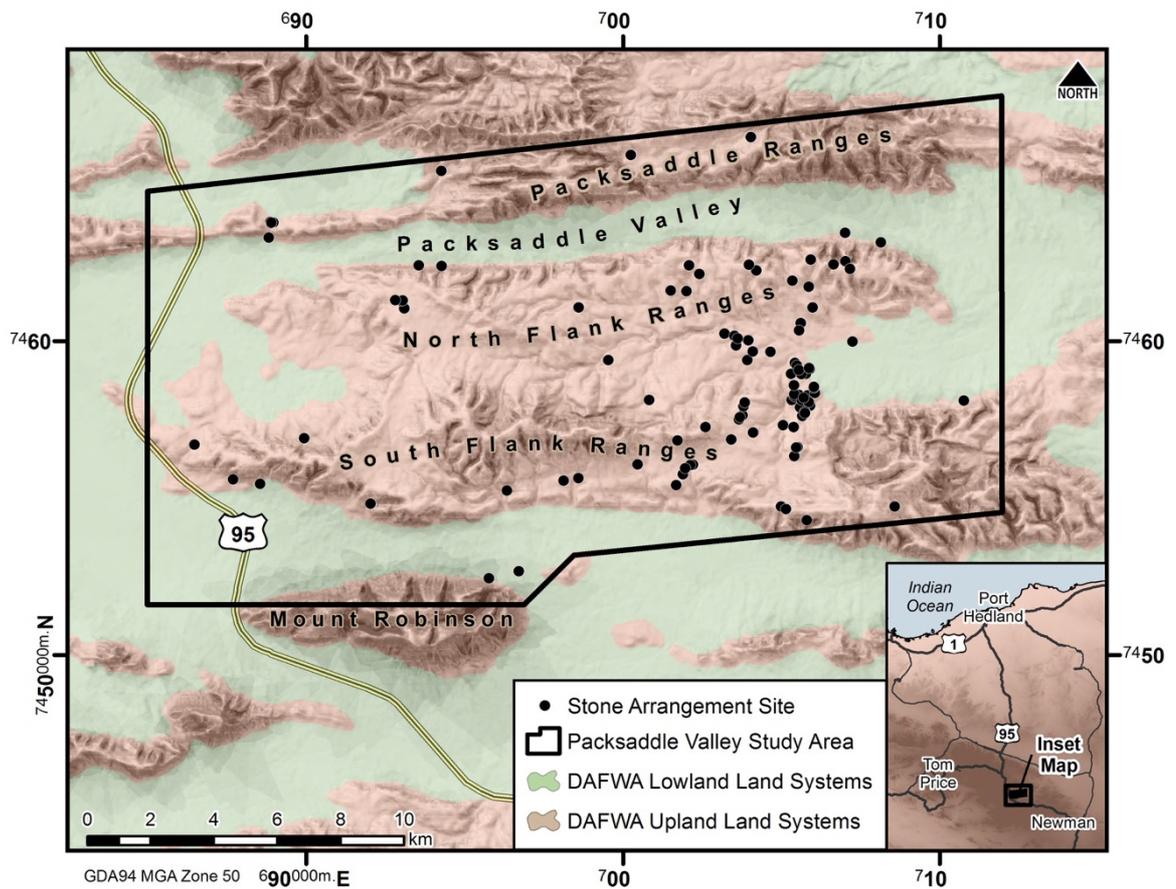


Figure 3-2 Packsaddle Valley study area map and land system classes, including locations of stone arrangement sites.

Table 3-1 Packsaddle Valley study area land system descriptions (after Van Vreeswyk et al., 2004).

Land System	Class	Description	km ²	Percentage of study area
Boolgeeda	Lowland	Dissected slopes and raised plains supporting hard spinifex grasslands. Topographic relief up to 20m.	92.5	25.4
Newman	Upland	Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands. Topographic relief up to 450m.	239.6	65.8
Pindering	Lowland	Gravelly hardpan plains supporting groved mulga shrublands with hard and soft spinifex. Topographic relief up to 10m.	6.9	1.9
Platform	Lowland	Dissected slopes and raised plains below ranges supporting hard spinifex grasslands. Topographic relief up to 30m.	11.4	3.1
Wannamunna	Lowland	Hardpan plains and internal drainage tracts supporting mulga shrublands and woodlands. Topographic relief up to 5m.	14.0	3.8

Topographically below the Newman Land System are the Boolgeeda, Pindering, Platform, and Wannamunna Land Systems (Table 3-1). Together, these lowland land systems occupy 34.2 percent of the study area. Topographic relief varies from 5m to 30m in these lower land systems. They are depositional environments, characterised by Quaternary colluvium and detrital ironstone gravels, and commonly referred to as ‘stony plains’ (Payne, 2004).

3.3.2 Stone Arrangements

Australian Aboriginal stone arrangements are a well-known archaeological site type documented throughout Australia. Horton (1994, p. 1029) points out that stone arrangements have been recorded in a wide range of forms, including “cairns, mounds, walls, lines, circles, crescents, loops, spirals, ‘horseshoes’ and rock-lined pits.” It has been further emphasised by Rowland and Ulm (2011) that fish traps and weirs are additional Aboriginal stone arrangement types with widespread continental distribution.

In Western Australia, the *Aboriginal Heritage Act 1972* defines stone arrangements as a ‘man-made structure’ distinguished by “the placement or arrangement, by Aboriginal people, of stone, wood or other material into a structure for ceremonial or utilitarian purposes.” In this study, the term ‘stone arrangement’ is used to describe a group of standing stones that have been positioned in a non-random pattern across an open land surface. Although single, isolated embedded stones are often reported as stone arrangements, single stone sites are not included in our research due to the possibility that a stone may have been uplifted via natural processes (e.g., tree roots or erosion) (Law, 2014a, 2014b).

A remarkably high number of Aboriginal stone arrangement sites have been documented in the central Hamersley Plateau, which includes the Packsaddle Valley area. The concentration of stone arrangement sites in the central plateau region is far greater than any other area of the Pilbara, with more than 180 sites reported (Figure 3-1). Undoubtedly the high frequency of documented sites is the result of intense archaeological survey coverage, as much of the area has been thoroughly surveyed for mining developments. Nonetheless, it is additionally plausible that the high density of stone arrangement constructions may be due to ancient Aboriginal cultural behaviours yet to be understood.

Approximately 95 percent of the Packsaddle Valley study area has been subject to pedestrian archaeological survey, resulting in a large sample of recorded stone

arrangement sites. According to heritage site records, there are 104 undisturbed stone arrangement sites in the current study area (Figure 3-2). These sites are in their natural landform context and have not been impacted by mining or other industrial activities.

Previous research indicates that nearly all Packsaddle Valley stone arrangements are constructed from banded ironstone or ironstone conglomerate, often with lateritic or pisolitic gravels (Hook, 1999; Hook & Di Lello, 2010; Hook et al., 2010; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b). Stone arrangements are normally constructed on relatively level ground surfaces, with the principal construction method involving the burial and upright vertical embedment of a stone. Occasionally, a stone may be positioned and placed atop of the ground.

Researchers further report that the maximum height of most embedded stones range 25-45cm above ground surface, with the buried base of embedded stones ranging 10-20cm below surface (Hook & Di Lello, 2010, p. 291). A previous review of stone arrangement records found that a typical stone arrangement site contains an average of 34 stones (Hook et al., 2010); however a recent desktop study, with a larger sample of site records, estimates an average of 23 stones per arrangement (Law, 2014a). Sites constructed with hundreds of stones, although uncommon, are also reported (Hook & Di Lello, 2010, p. 291; Hook et al., 2010).

Linear and curvilinear designs of stone arrangements are the most common regionally (Figure 3-3); however, amorphous designs and cairns also occur (Figure 3-3). Positioned stones have been documented as spanning a few meters, or they can potentially stretch to more than 100 meters in total length (Hook et al., 2010). In the latter instances, the stone arrangement may involve hundreds of embedded stones (Hook & Di Lello, 2010; Hook et al., 2010; Hook et al., 2002; Quartermaine, 1996a, 1996b). There are no examples of any stones having been physically modified in the construction of arrangements in Packsaddle Valley area.

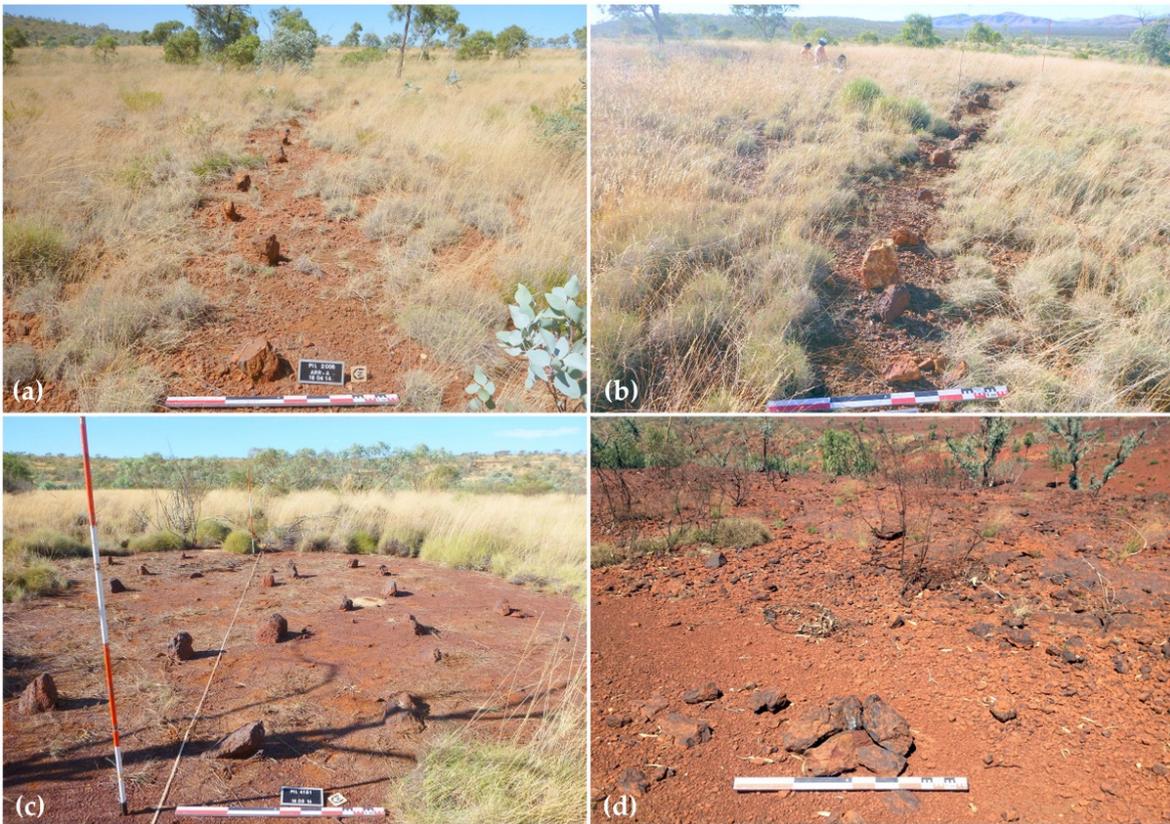


Figure 3-3 Examples of Packsaddle Valley stone arrangement design types. Generalized design categories include (a) linear, (b) curvilinear, (c) amorphous, and (d) cairn (Photographs: J. Brindley). Variations in design type categories are common regionally.

The precise antiquity and function of stone arrangements is poorly understood. Preliminary optically stimulated luminescence dates suggest most stone arrangements were constructed in the past 300 years; however further analysis is recommended (Hook & Di Lello, 2010; Hook et al., 2010). Ethnographic data are often cited to imply function, leading many archaeologists to speculate that stone arrangements were constructed for ceremonial and mythological purposes, although utilitarian functions are also possible in some instances (Gould, 1969; Hook & Di Lello, 2010; Law, 2014a, 2014b; Quartermaine, 1996a).

3.4 MATERIALS AND METHODS

The georeferenced locations of 104 stone arrangement sites in the Packsaddle Valley study area were used in this study. The two key information sources used to produce the digital terrain model were: 1.) the 1 arc-second Advanced Land Observation Satellite (ALOS) Global World 3D – 30m (AW3D30) DSM dataset and 2.) the DAFWA Pilbara Land Systems spatial data. ESRI’s ArcGIS 10.3 with the Spatial Analyst extension was used to analyse all spatial and remote sensing data associated with this research.

The AW3D30 DSM dataset is a free raster product available from the ©JAXA Earth Observation Research Centre web portal (<http://www.eorc.jaxa.jp/ALOS/en/aw3d30/>). It is based on elevation data acquired via the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM), a sensor mounted aboard the ALOS during its mission between 2006 and 2011. The AW3D30 DSM dataset has been post-processed and vertically corrected against JAXA's high resolution 5m mesh DSM of the ALOS World 3D Topographic Data (Tadono et al., 2014; Takaku et al., 2014). The resulting AW3D30 DSM dataset offers $\pm 5\text{m}$ vertical height accuracy, making it amongst the most accurate elevation datasets available at 30m horizontal resolution. Thus, it is a spatially averaged product of the combined 30m DSM and 5m DSM ALOS datasets. Although it is a DSM product and does not exclusively represent bare-earth elevation data, the DSM measurements have negligible effect on our study because of the lack of tall or dense tree canopies and buildings in the study area. The local arid environment precludes the growth of a significant vegetation overstorey that could obscure satellite measurements, and there are few building structures in the study area. Still, to minimise elevation irregularities, the AW3D30 DSM data was further processed using a mean focal statistics filter (90m circular radius) to reduce image noise and smooth vegetation/land surface features. We additionally omitted the industrial zone from the AW3D30 DSM dataset to ensure mining infrastructure and altered ground surfaces did not affect the classification results.

The DAFWA digital land systems data are the second set of spatial information used in the digital terrain model. The DAFWA data corresponds with an encyclopaedic environmental study of the Pilbara biogeographic region (Van Vreeswyk et al., 2004). Pilbara land system maps can be viewed at the DAWFA web portal (<https://www.agric.wa.gov.au/maps-and-data>), and the spatial data are available to researchers under licensed agreement with the state government. It is a vector-based dataset, containing the spatial boundaries and descriptions for the Pilbara land system classes as defined by Van Vreeswyk et al. (2004).

A number of geomorphometric classification methods have been proposed to discriminate topographic slope position and digitally classify land surfaces (e.g., De Reu et al., 2013; Deumlich et al., 2010; Iwahashi & Pike, 2007; Miller & Schaetzl, 2015; Riley et al., 1999; Weiss, 2001). This project adopts the classification methodology espoused by Deumlich et al. (2010) and utilises the ArcGIS Relief

Analysis toolbox extension developed by Miller (2015) to construct the topographic slope position model.

The two variables used to categorise land surfaces into their respective topographic slope position class are the Topographic Position Index (TPI) and slope gradient (degrees). These variables were calculated in ArcGIS using the AW3D30 DSM mesh grid elevation values. A circular neighbourhood radius of 120m was used in the calculation of the TPI values, and the slope gradient was computed for each individual grid cell. The measured TPI and slope values were saved as separate raster files and entered as independent variables in the digital classification of the topographic slope position, discussed below.

Miller’s (2015) Relief Analysis toolbox was used to digitally categorise the TPI and slope gradient values into the topographic slope position classes designated by Deumlich et al. (2010) (Table 3-2). For our study, we replaced the term ‘valley’ with ‘gully or scree slope’ to better reflect local Pilbara land features. Another significant difference with the Deumlich et al. (2010) method is the use of digital land system data to topographically differentiate flat upland surfaces (Class 4) and flat lowland surfaces (Class 5) classes (Table 3-2). This was achieved using the DAFWA land system polygons as a grid cell extraction and reclassification mask in the final stage of the analysis. Thus, the digital land system data functioned to delineate and reclassify the topographic slope position of flat ground surfaces in upland land systems from flat surfaces in lowland land systems (Figure 3-2).

Table 3-2 Topographic Slope Position classification criteria.

Class	Description	TPI	Slope	Land System
1	Summit, Hilltop, Ridge	> 1		
2	Upper Slope	> 0.5 ... ≤ 1		
3	Midslope	> -0.5 ... < 0.5	>2°	
4	Flat Upland Surface	≥ -0.5 ... ≤ 0.5	≤2°	DAFWA Upland L.S. Mask
5	Flat Lowland Surface	≥ -0.5 ... ≤ 0.5	≤2°	DAFWA Lowland L.S. Mask
6	Lower Slope	≥ -1 ... ≤ 0.5		
7	Gully, Scree Slope	< -1		

The ‘flat surface’ class is a potentially problematic category to classify with the algorithm, as the equation does not differentiate the topographic context of ‘flat surfaces.’ For example, the algorithm classifies the topographic slope position of a flat stony plain in the same manner as a flat hilltop land surface. The ‘flat surface’ class can thereby be misleading if the topography cannot be discriminated. The DAFWA digital land systems data resolves this potentially problematic scenario, allowing for ‘flat upland surface’ and ‘flat lowland surface’ slope classes to be

distinguished. The 'flat upland surface' class is interpreted to be broadly flat hilltop or hillslope areas, mesas, and other relatively level upland ground surfaces. Stony plains and alluvial flats are considered to be 'flat lowland surfaces' that are topographically below upland land systems.

With the digital terrain model complete, the final stage of the analysis compared the Packsaddle Valley stone arrangement site locations with the modelled topographic slope position classes. ArcGIS was used to calculate land area (sq. km) for each topographic slope position class and extract the topographic slope position class values for each georeferenced stone arrangement site centroid (n=104). As outlined by Kvamme (1997), a Chi-square goodness-of-fit statistical analysis was used to test the non-random nature of the stone arrangement spatial patterning. The goodness-of-fit statistical method cross-tabulates the observed and expected stone arrangement sites frequencies against topographic slope position classes, thus testing the null hypothesis that stone arrangement sites are evenly distributed across all classified land units. In addition to this Chi-square test, a simple site frequency ratio was calculated comparing observed and expected number of stone arrangements. It enables a meaningful comparison of stone arrangement distribution for each topographic slope position class regardless of land area size.

3.5 RESULTS

The resulting digital terrain model of topographic slope position classes, with stone arrangement site locations is presented in Figure 3-4. The figure demonstrates that stone arrangement locations are highly correlated with upper topographic slope positions. The extracted raster values presented in Table 3-3 indicate 85.6% of stone arrangement sites occur in upper topographic contexts, with stone arrangements observed on the summit/hilltop/ridges (38.5%), upper slopes (16.3%), midslopes (15.4%), and flat upland ground surfaces (15.4%) on hilltop and hillslopes. Stone arrangements were observed less frequently in lower topographic settings such as gullies (9.6%), lower slopes (2.9%), and flat lowland surfaces (1.9%) like stony plains (Table 3-3).

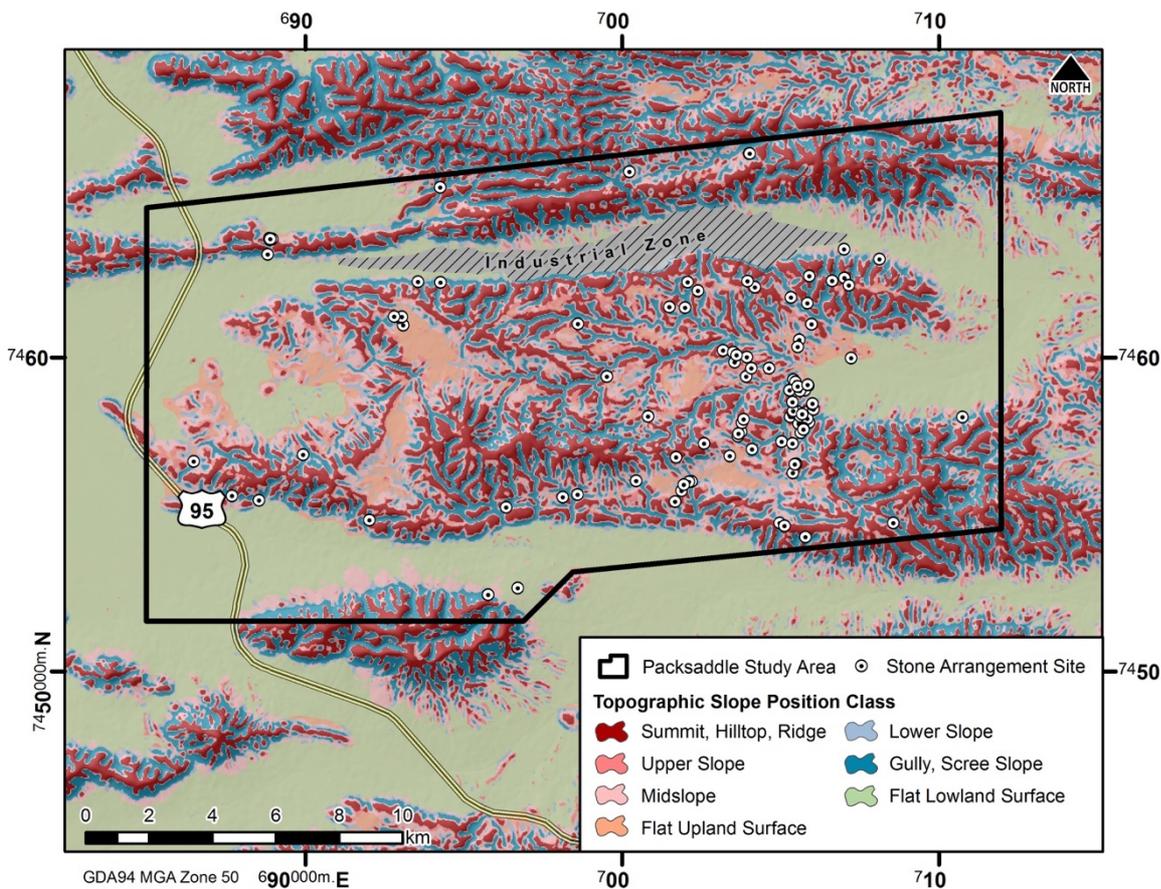


Figure 3-4 Topographic slope position classes for the Packsaddle Valley study area.

Table 3-3 Frequency statistics of Packsaddle Valley stone arrangements by Topographic Slope Position Class and study region land area.

Topographic Slope Position Class	Stone Arr. (n)	Stone Arr. (%)	Land Area (sq. km)	Land Area (%)
Flat Lowland Surface	2	1.9	88.4	24.3
Gully, Scree Slope	10	9.6	64.9	17.8
Lower Slope	3	2.9	28.9	7.9
Midslope	16	15.4	49.5	13.6
Flat Upland Surface	16	15.4	16.8	4.6
Upper Slope	17	16.3	26.0	7.1
Summit, Hilltop, Ridge	40	38.5	74.8	20.5
Industrial Zone*	0	0.0	15.1	4.1
Total	104	100	364.4	100

*Land redevelopments preclude definitive classification due to infrastructure and altered natural ground surfaces.

This spatial pattern is not random, and it is not the result of over-representation of any particular topographic slope position class in the study area. The Chi-square goodness-of-fit test performed against the observed and expected site values in Table 3-4 determined that stone arrangement sites are not equally distributed across all topographic slope position classes, $X^2 (df = 6, N = 208) = 79.536, p < 0.001$. The results further suggest that Packsaddle Valley stone arrangements are more likely to be constructed on upper topographic contexts. This observation is best articulated in the Table 3-4 site frequency ratio column. The

ratios indicate that stone arrangements are most likely to occur on flat upland surfaces (3.20), followed by upper slopes (2.13), summit/hilltop/ridge (1.82), and midslope classes (1.07) (Table 3-4). In comparison, lower topographic contexts are far less likely to have stone arrangement constructions, with lower slopes (0.33), gully scree slopes (0.53), and flat lowland surfaces (0.08) having comparatively low ratio values (Table 3-4).

Table 3-4 Observed and expected site frequency and ratio statistics for Packsaddle Valley stone arrangements by Topographic Slope Position Class and study region land area.

Topographic Slope Position Class	Land Area* (%)	Observed (O) Sites	Expected (E) Sites	Ratio O/E
Flat Lowland Surface	25.3	2	26	0.08
Gully, Scree Slope	18.6	10	19	0.53
Lower Slope	8.3	3	9	0.33
Midslope	14.2	16	15	1.07
Flat Upland Surface	4.8	16	5	3.20
Upper Slope	7.4	17	8	2.13
Summit, Hilltop, Ridge	21.4	40	22	1.82
Total	100	104	104	-

*Note the total classified land area is 349.3 sq. km, as the industrial zone in Table 3-3 precludes classification of 15.1 sq. km.

3.6 DISCUSSION

Stone arrangements in the Packsaddle Valley have been investigated and recorded by numerous field archaeologists over the past three decades, each with variable expertise in geomorphology. Consequently, some government site records have been lodged with erroneous or misconstrued topographic setting assessments and, in many instances, previous investigators have not used any standardised geomorphic classification system. The variable quality of past recordings has led to a skewed understanding of where stone arrangements occur in the landscape.

Official site records lodged with the DAA indicate that stone arrangements may be constructed on any geomorphic land unit; however, a review of 73 DAA records by Hook et al. (2010, pp. 29-31; 36-37) revealed that Packsaddle Valley stone arrangements are most often reported in lower topographic settings such as valley plains (n=23, 31.5%) and hill bases (n=19, 26.0%). Their contracted study also reports that some stone arrangements have been constructed on low rises (n=3, 4.1%), presumably in lowland settings, although the DAA records do not specify. Hook et al. (2010) further document that a small proportion of stone arrangements occur on upland hillslopes (n=12, 16.4%) and ridges (n=11, 15.1%). A small percentage of government records (n=5, 6.8%) lacked any information on the topographic location of stone arrangements (Hook et al., 2010).

More recently, a desktop study was commissioned for the purpose of synthesizing all available site details on stone arrangements in the greater Packsaddle Valley region (Law, 2014a). The study produced a large database of site records (n=108) in the vicinity of our study area. The database includes original DAA files and unpublished material submitted by several consultants between 2010 and 2014. In total, 92 site descriptions contained sufficient information to topographically classify stone arrangements, but the study findings were significantly different to previous research. The records indicated that stone arrangements are more common on upper topographic settings, a stark contrast to the Hook et al. (2010) record review. Law's (2014a, pp. 42-46) collation of previously documented site details indicated that the majority of stone arrangements occur in hilltop/ridges (n=46, 50.0%), followed by hillslopes (n=13, 14.1%), toeslopes (n=6, 6.5%), plains (n=13, 14.1), and terraces (n=14, 15.2%). Law (2014a) attributed the contrary results to a larger site record sample size, the availability of more recently updated site information, observer-recorder biases, variability in geomorphic expertise, and erroneous stone arrangement identification (e.g., natural erosion or tree uplifted rock).

Our study resolves the contradictory findings of earlier reviews, and we argue that digital terrain models are a more objective and accurate representation of topographic context. For the Packsaddle Valley land surfaces, geomorphometric analysis supersedes previous assessments of site topography. The digital terrain model is not impeded by the subjective field observations of multiple site recorders, offering a more consistent approach for determining the topographic slope position of stone arrangements. It unambiguously demonstrates that stone arrangements are more likely to be constructed in upper topographic land surfaces, resolving the contrasting patterns reported by previous researchers and contributing to greater understanding of stone arrangement spatial patterns in the Packsaddle Valley region.

Future heritage surveys will benefit from the knowledge that Packsaddle Valley stone arrangements are most likely to be constructed on flat upland ground surfaces, followed by upper slopes, summit/hilltop/ridges, and midslopes (Table 4). This information will give researchers better grounding for developing and testing hypotheses and landscape archaeology models. Land managers will be able make more informed heritage decisions, and Aboriginal stakeholders may corroborate this information with their traditional knowledge to advise policy makers on

conservation issues. Furthermore, our digital terrain model is also a significant step towards developing a predictive model for investigating stone arrangement distribution regionally, particularly in unsurveyed areas.

This research may also increase our insights on the range of possible functions and human behaviours associated with the Packsaddle Valley stone arrangements. For instance, could it be that stone arrangements are common in uplands due to the practicalities of construction? Larger stones are easier to procure in uplands, and ironstone slabs are abundant due to frequent bedrock exposures. It is far easier to construct stone arrangements nearer to the raw material source. In comparison, it would require considerable energy and commitment to transport stones weighing more than 20kg stones long distances onto plains and similarly low topographic settings. Traditional Aboriginal hunter-gatherer societies were highly mobile by nature and tended to optimise transport costs. Moving heavy stones long distances to construct arrangements would not seem in character with traditional mobility practices.

Pragmatic behaviours aside, is there a cultural motivation for why stone arrangements are concentrated in upper topographic settings? Many of the sites are positioned on land surfaces with breathtaking views of the surrounding landscape, giving stone arrangements a monumental quality. Admittedly, this observation is an aesthetic attribute that cannot be impartially quantified; however, there is ethnoarchaeological and anthropological evidence that suggests some stone arrangements functioned as totemic or mythological monuments. Could it be that the selected topographic setting of some sites is related to this function?

Gould's (Gould, 1969, 1980) ethnoarchaeological research with the Nyatunyatjara people of Western Australia's Gibson Desert indicates that some stone arrangements may have totemic mythological significance. Gould (1969, p. 144) enquired with many Aboriginal elders on the function of a 'serpentine-shaped' arrangement, concluding that "Rock alignments and artificial rockpiles are consistently interpreted as the bodies or paraphernalia of totemic beings changed by themselves into lithic form."

If Gould's assessment transcends Aboriginal cultural boundaries, then perhaps some of the Packsaddle Valley stone arrangements functioned as totems or mythological monuments, and their elevated position in the landscape may be related to this function. Local anthropological research by Palmer (1977) deduced

that several Packsaddle Valley stone arrangements are mythological sites, related to the Dreamtime movements of a mythological spirit being. Thus, based on this information, it does not seem unreasonable that the topographic context of some stone arrangement sites is related to their monumental function. This hypothesis is admittedly founded on anecdotal evidence, but we believe that the data are compelling enough to warrant further research. In the least, this research does highlight that the spatial sciences have an important role to play in future studies of ancient Aboriginal stone arrangements.

Although the range of possible functions for Packsaddle Valley stone arrangements remains enigmatic, our study on the topographic distribution of stone arrangements is a crucial first step for understanding where stone arrangements occur in the local landscape. This baseline information will undoubtedly contribute to future research of this unique class of Aboriginal cultural phenomena.

3.7 CONCLUSIONS

Although this example focuses on Australian subject matter, our research methods have applicability to practitioners of landscape archaeology worldwide, especially in regards to site distribution studies. Satellite-derived elevation models and digital land system data are increasingly accessible to archaeologists at no cost, enabling researchers to create custom digital terrain models of virtually any landscape on Earth. In this example, we have demonstrated how digital elevation data and land systems information can be used to discriminate the topographic setting of Packsaddle Valley Aboriginal stone arrangements. Contrary to previous site records, we have established that Aboriginal stone arrangements are generally constructed in upper topographic contexts. We have speculated that the reason for this pattern is possibly due to the practicalities of resource distribution or perhaps due to unknown ancient totemic or mythological purpose. Other utilitarian functions of stone arrangements are also plausible and likely, but additional research in this area is required.

The Packsaddle Valley digital terrain model is a more objective representation of the topographic context of land surfaces, and our digital classification method is more consistent than the varied field observations of past site recorders. Despite the fact that we do not conclusively understand the function of stone arrangements, this research has proved worthwhile in demonstrating that we do understand much

about their distribution in the landscape. Future predictive modelling studies will invariably benefit from the spatial patterns revealed in this study.

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3.9 AUTHOR CONTRIBUTIONS

In collaboration with BHPBIO and the Banjima Native Title Claimants, M.J.S. and W.B.L. conceived the research project and supervised fieldwork; W.B.L. conducted the background research, designed the methodology, and performed the spatial analysis; W.B.L. wrote the paper and prepared the figures and tables; M.J.S. contributed to the interpretation and discussion of the results. M.M.L. provided technical and stylistic edits and contributed to the document organisation, structure, and statistics. B.O. offered additional technical edits and advised on the geospatial and statistical methods employed in this document.

3.10 CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Contribution to the Paper	W.B.L. is the principal author, creator, and spatial science technician behind this study. He drafted the original version of the paper and created all of the figures in the paper. Through collaboration with his co-authors, integrated their comments, contributions and edits into the final document.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	25/3/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

- i. the candidate's stated contribution to the publication is accurate (as detailed above);
- ii. permission is granted for the candidate to include the publication in the thesis; and
- iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Signature		Date	25/3/2020

Chapter 4 Reflecting on Siliceous Rocks in Central Australia: Using Advanced Remote Sensing to Map Ancient 'Tool Stone' Resources

4.1 ABSTRACT

HyMap™ airborne hyperspectral imagery was used to discriminate and map hydrated silica mineralisation in the Dalhousie Springs area of central Australia. A spectral feature fitting algorithm was used to match laboratory reference spectra with image pixel spectra, producing a scaled goodness-of-fit raster map of silicified “tool-stone” sources in our study area. Subsequent fieldwork indicated that the algorithm mapped silcrete, a rock composed of hydrated silica, and incidentally, the most frequently utilized raw material for stone artefact manufacture in this area of the Australian arid zone. The soundness of our hydrated silica mineralisation map is supported with field observations and spectroscopic analysis of collected silcrete samples. Independent siliceous rock mapping produced by the Commonwealth Scientific and Industry Research Organisation offers additional corroboration of our results. Based on the success of our approach, we suggest that archaeologists working in Australia and in similar arid environments elsewhere have much to benefit in using advanced remote sensing products to map lithic resources, including time and cost-saving advantages for field logistics, enriched assessments of land suitability for archaeological site types, and an improved understanding of resource distributions.

4.2 INTRODUCTION

Accurately identifying where lithic raw materials suitable for stone artefact manufacture can be sourced is a prominent theme in Australian Aboriginal archaeology and landscape archaeology worldwide (e.g., Bird, 1985; Carr & Turner, 1996; Clarkson & Bellas, 2014; Davies et al. 2016; Duke & Steele, 2010; Fanning et al 2009; Gould & Saggars, 1985; Hughes et al., 2014; Megarry et al., 2016; Newman, 1994; Sullivan et al. 2014; Tanyaş et al., 2017; Thiry & Milnes, 2017; Tibbett, 2002). Raw material provenance offers archaeologists a foundation and scale to begin geographically investigating stone artefact technology and prehistoric lithic procurement practices. An accurate understanding of raw material distribution also informs researchers of relative resource abundance and provides insights of past land-use practices and subsistence-settlement strategies. In conjunction with additional spatial information (e.g., slope, aspect, topographic position index,

drainages), this information is also useful in developing site suitability models for specific archaeological site types, including prehistoric quarry sites and lithic procurement localities.

Traditionally, researchers have relied upon geological maps, geomorphology, artefact attributes, and conventional petrological characterisation through methods such as thin section analysis to identify the origin of lithic raw materials. Pinpointing raw material sources is often a time-consuming and labor-intensive exercise, so for the sake of expedience, it is not uncommon for researchers to generalize raw material classes as endemic to particular geographic regions, geological formations, or land units without definitive evidence. Occasionally, some researchers are fortunate to work in areas with previously recorded lithic quarrying sites and well-documented geological outcrops (Attenbrow et al. 2017; Byrne, 1980; Douglass & Holdaway, 2011; Gould & Saggars, 1985; Lamb, 2011; McBryde, 1984; McBryde & Harrison, 1981). However, due to the vast scale of central Australian landscapes, it is relatively rare for archaeologists to have a firm knowledge of the location of specific raw material sources.

Geological mapping in remote areas of the Australian arid zone is typically limited to 1:250,000 scale maps. A lack of more detailed mapping often results in researchers ascribing generalized lithic provenance to stone artefact specimens during analysis. For instance, Australian researchers often divide lithic assemblages into local, intermediate, nonlocal, or “exotic” raw material groupings, thereby inferring the distance to the resource origin (e.g., Gould & Saggars, 1985; Law, 2009; Smith, 2006; Veth, 1993). The analytical practicalities of this approach are obvious; however, the accuracy and robustness of such inferences are variable, with groupings sometimes based on informed “best guesses.”

One way that modern science may contribute to mapping lithic resources is through the use of advanced remote sensing. Remote sensing is the science of obtaining information about objects and materials resting on the Earth’s surface via imaging sensors mounted on aircraft and satellites (Campbell & Wynne, 2011; Harrison et al., 2016; Lillesand & Kiefer, 2006). Since the 1970s, remote sensing scientists have used multispectral and hyperspectral image products to discriminate and map geological materials (Chen & Campagna, 2009; Drury, 2001; Gupta, 2018; van der Meer et al., 2012). The principles underscoring the use of passive optical remote sensing for geological mapping are straightforward. All materials on the Earth's surface reflect, absorb, and scatter solar radiation. The electromagnetic

radiation interacts with the surface geological materials, and due to molecular bonds in the material's underlying chemistry, many minerals will absorb and reflect light in a unique manner. Sensors on aircraft and satellites passively measure the energy reflected from all surface materials and record this information in a multilayered raster image. A hyperspectral image or datacube may contain more than a hundred image layers, each of which has measured reflectance for a narrow band of the visible and shortwave infrared light spectrum (see Pu, 2017, pp. 2–3). Collectively, a hyperspectral datacube contains a detailed spectral reflectance curve for each pixel in the image. The shape of the spectral curve is indicative of mineralogy of the surface material, and in the right context, it can serve as a diagnostic marker to identify the material (see Pu, 2017, pp. 6–7). This is why the distinctive features of a material's spectral reflectance are often referred to as its “spectral signature.” Using image analysis software, the spectral signature of a particular mineral can be queried and matched against the image spectra, highlighting which pixels have spectra closely matching the spectral properties of the reference material. Since the raster image is georeferenced, the output image is effectively a map showing a material's relative abundance and distribution in the landscape.

Silica-rich (SiO_2) lithic materials are of considerable interest to archaeologists worldwide, as siliceous rocks often have favorable fracture mechanics for flintknapping purposes. In central Australia, silcrete is a sought after siliceous raw material for stone artefact manufacture due to its proclivity for controlled conchoidal fracture and its relative abundance in some areas. Silcrete is a fine to coarse-grained silicified rock. Fine-grained varieties of silcrete commonly fracture with a vitreous luster and are more suitable for controlled flake detachments. However, medium and coarse-grained silcretes may also be utilized for flaked stone artefact manufacture.

Silcrete forms when unconsolidated regolith (e.g., sediments, saprolite, soils) is cemented by secondarily deposited silica through a process known as silicification (Callen, 1983; Milnes & Thiry, 1992; Summerfield, 1983; Taylor & Eggleton, 2017; Wopfner, 1978). Petrological studies indicate the siliceous mineral cement is a combination of amorphous, cryptocrystalline, and microcrystalline forms of silica, ranging from granular to fibrous (chalcedonic) crystalline structures (Hughes et al., 2014; Milnes & Thiry, 1992; Taylor & Eggleton, 2017; Thiry & Milnes, 2017; Thiry, Fernandes, Milnes, & Raynal, 2014). These microscopic forms of silica are frequently associated with a family of hydrated silicate minerals that include opal,

chalcedony, agate, and other types of microquartz (Flörke, Graetsch, Röller, & Wirth, 1991; Graetsch, Flörke, & Miehe, 1985; Smith, Bandfield, Cloutis, & Rice, 2013). Remote sensing scientists commonly describe this family of minerals as “hydrated silica,” a term that points to their aqueous formation history and refers to trace interstitial water and hydroxyl groups trapped in their crystalline structure (e.g., Flörke et al., 1991; Graetsch et al., 1985; Smith & Bandfield, 2012; Smith et al., 2013). Research has shown that rocks with hydrated silica mineralogy have unique spectral characteristics that enable them to be discriminated in aerial and satellite hyperspectral imagery (Kokaly et al., 2017; Livo et al., 2007; Milliken et al., 2008; Smith & Bandfield, 2012; Smith et al., 2013; Swayze et al., 2014; Vaughan et al. 2005). Thus, since hydrated silica is involved in the formation and underlying mineral structure of silcrete, hyperspectral remote sensing may be useful for mapping the distribution, context, and abundance of silcrete, and/or related silicified rocks. This kind of information could potentially assist researchers with assessments of landform suitability for specific archaeological site types (e.g., artefact quarries and lithic reduction sites) and aid with investigations concerned with the spatial proximity of sites to lithic resources.

In the past decade, there has been an increase in the availability of advanced remote sensing image products (including hyperspectral and multispectral imagery), offering Australian archaeologists new tools to discriminate rocks and minerals based on their spectral characteristics. In this paper, we describe how high-resolution airborne hyperspectral imagery was used to map silcrete lag gravels around Dalhousie Springs, an artesian mound spring complex located in central Australia. Silcrete is a well-documented raw material used by Aboriginal peoples in the region; thus, it is an ideal test case to investigate the suitability of hyperspectral mapping for Australian archaeology and similar hunter-gatherer archaeological studies worldwide.

4.3 BACKGROUND

Studies have shown that hyperspectral remote sensing can identify and broadly map hydrated silica-bearing rocks via a distinctive spectral feature in the shortwave infrared (SWIR) part of the electromagnetic spectrum (Ehlmann et al., 2009; Kokaly et al., 2017; Livo et al., 2007; Milliken et al., 2008; Smith & Bandfield, 2012; Swayze et al., 2014). More specifically, research indicates that a broad spectral absorption feature centered around 2.21–2.26 μm can discriminate hydrated silicate

minerals, including agate, opal, chalcedony, and microquartz (Ehlmann et al., 2009, p. 13; Livo et al., 2007, p. 495; Smith & Bandfield, 2012, p. 2; Smith et al., 2013, p. 637; Swayze et al., 2014, p. 1199). Since these mineral forms, in varying proportions, constitute the siliceous cement that indurates silcrete, we hypothesize that the spectral signatures of these minerals can be used to effectively discriminate and map silcrete or similar silicified rocks.

4.3.1 Study Area

The Dalhousie Springs complex (DSC) study area is located in Witjira National Park (GDA94/53J/544424mE/6951456mN), a South Australian Government-managed reserve in central Australia (Figure 4-1a). The boundary of the DSC study area, as illustrated throughout Figure 4-1, is dictated by the maximum extent of the remote sensing imagery utilized in this study, which measures close to 20.0 km E-W by 25.5 km N-S. The total area of land inside the DSC polygon is 375 km².

The DSC occupies a remote and arid region of Australia, receiving on average less than 200 mm of rainfall annually. Historic weather data from the Australian Bureau of Meteorology's nearest weather station (Oodnadatta, South Australia) indicates the region has a mean annual rainfall of 176.4 mm. Summers are extremely hot and dry, with a mean maximum daytime temperature of 37.9°C (January). Winters are cool to cold, with a mean maximum July daytime temperature of 19.7°C.

The DSC study area is named after a cluster of artesian “mound” springs that discharge from the western Great Artesian Basin (GAB). It is the most northerly group of artesian springs in South Australia, and it is arguably the most ecologically-rich spring complex in the GAB, creating the most extensive and diverse spring-fed wetlands in the eastern arid zone (White & Lewis, 2011, p. 141). The DSC has been intensively surveyed, with at least 145 spring vents recorded in detail (Gotch, 2013b, p. 119; Gotch, 2013a; White et al., 2013). The springs are a refuge for several distinctive species of flora and fauna that have evolved in isolation and are globally unique. Accordingly, the DSC was added to the Australian Government Register of the National Estate in 2009, and it is also recorded on the National Heritage List.

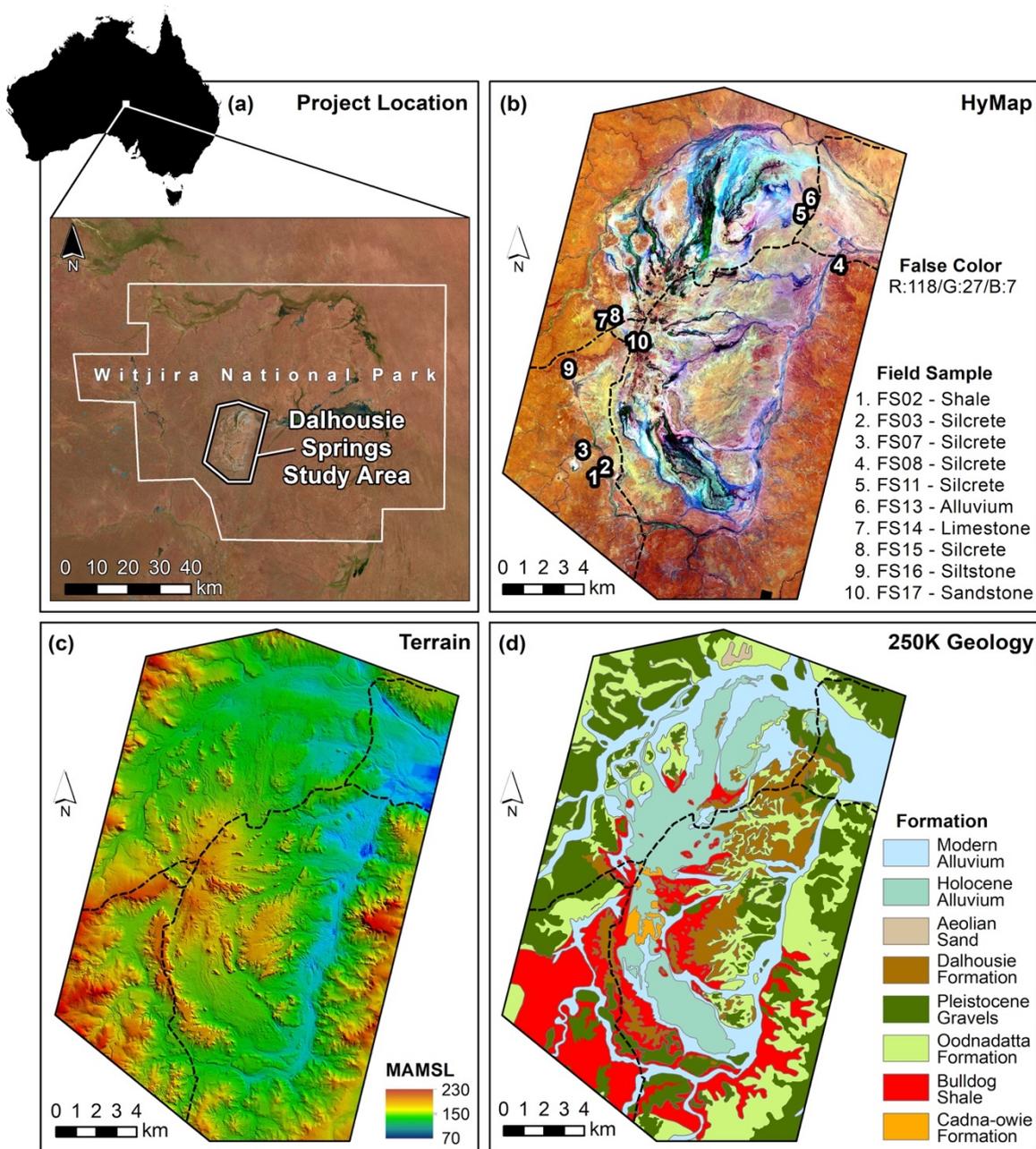


Figure 4-1 (a) Location map for Witjira National Park and the Dalhousie Springs Complex study area. (b) False-colour HyMap hyperspectral image (band combination: R:118, G:27, B:7) of study area emphasizing surface regolith and “oval-shape” of lower central anticline area. Provenance of field samples subject to laboratory spectroscopy is also noted. (c) Terrain height topographic map derived from high-resolution DEM UltraCam digital orthophotography (Lewis et al., 2013) and represented as meters above average mean sea level (MAMSL). (d) Dalhousie 1:250,000k Surface Geology Map (SG/53-11) as mapped by the South Australian Geological Survey (Krieg, 1985; PIRSA, 2012)

The springs are a permanent and reliable desert water source, so it is understandable that they are important to local indigenous groups, including the Southern Arrente (also spelled Aranda), Wangkangurru, and members of the Irrwanyere Aboriginal Corporation. Mythological stories, songs, and sites of high cultural significance are associated with the springs (Ah Chee, 2002; Harris, 2002; Hercus, 1990; Hercus & Sutton, 1985; Potenzy, 1989), and numerous stone artefact

scatters are reported throughout the project area, including stone tool types (e.g., tulas, backed artefacts, and points) consistent with middle to late Holocene stone artefact technologies (Lampert, 1985, 1989). Based on radiometric dates from archaeological sites in similar ecological areas of far north South Australia, it is likely that Aboriginal people have subsisted in the springs region for at least the past 5,000 years (Hughes & Hiscock, 2005; Hughes et al., 2011; Sullivan et al., 2012), but in light of recent archaeological finds elsewhere in the South Australian desert, a much earlier Pleistocene occupation of the springs area is not an unreasonable proposition (e.g., Hamm et al., 2016; Hughes et al. 2017).

4.3.2 Geomorphological and Geological Setting

The DSC formed in a depression that resulted from the gradual weathering and erosion of a breached anticline (Krieg, 1982; Wolaver, 2013; Figure 4-1b). The main springs complex is topographically lower than the surrounding stony plain, known colloquially as the “gibber” plain. Mesas and tablelands rise above the gibber plain, forming the Emery Range immediately west and southwest of the DSC study area.

Gibber plains have low topographic relief and skirt along the periphery of the study area (Figure 4-2). They are sparsely vegetated with herbaceous chenopod species (Boyd, 1990; Purdie, 1984). The gibber surface is a densely packed desert pavement of highly weathered relict duricrust pebbles and cobbles on a deflationary surface (Fujioka et al., 2005). In the Dalhousie Springs area, the gibber is comprised of rounded to subrounded silcrete lag gravels, likely derived from the Cordillo Silcrete Formation that caps the Emery Range.

The central DSC study area, where the artesian spring complex occurs, is around 30–60 m lower in elevation (~120 m AMSL) than the surrounding gibber plain (Figures 3-1c and 3-2). The flat topography of the spring complex is interrupted by travertine mounds that have built up from the precipitation of mineral-rich spring waters. A blanket of alluvial sediment covers much of this lowland section of the study area, making it an unlikely location for natural occurrences of silcrete. Water drainage is poorly coordinated throughout the spring complex, but surface run-off progressively drains towards a great expanse of dunefields located east and northeast of the study area.



Figure 4-2 Photo of the dense silcrete gravels occupying the surface of the stony plain (foreground) and the alluvial lowland (background) occupying the central DSC study area. The silcrete-capped mesas along the skyline (Emery Ranges) are outside the study area. A colour version of this figure is available in the online PDF. DSC, Dalhousie Springs complex

According to the Dalhousie 1:250,000k map sheet (SG/53-11), the surface geology of the DSC study area is represented by at least eight distinctive geological formations, summarized in Figure 4-1d (Krieg, 1985; PIRSA, 2012). The oldest geological surface is the Early Cretaceous Cadna-owie Formation, a brown sandstone with coarse-grained beds that transition to finer-grain sandstone in its upper profile (Benbow, 1981; Krieg, 1985; Wopfner et al., 1970, p. 397). It is conformably overlain by the Bulldog Shale and Oodnadatta Formations, which are also Cretaceous-age marine-deposits. These formations underwent substantial weathering during the Tertiary, providing environmental conditions conducive to the formation silcrete in much of the central Australian regolith exposed at this time. The Quaternary is characterized by continued gradual weathering of the landscape, leading to the formation of gibber plains and Pleistocene gravel deposits. Mound spring activity initiated in the central study area during this time, contributing to the aggradation of alluvium in the lower spring areas (Krieg, 1989).

Of interest to this study are the formations mapped as the “Bulldog Shale” and “Pleistocene gravels.” Previous descriptions of these formations indicate that they likely to contain siliceous raw materials suitable for stone artefact manufacture (Krieg, 1985, 1989). The Bulldog Shale has been described as a dark gray mudstone and fossiliferous shale with occasional limestone interbeds (Krieg, 1985). Surface remnants of this formation occur in the southern and western study area, where

stratigraphic exposures of the shale are visible along low-rising escarpments and breakaways. Petrified wood, marine shell, and fossilized dinosaur bone (silicified with opal and chalcedony) have been observed in the upper lithofacies of the Bulldog Shale (Benbow, 1981; Pewklian et al. 2008). Hughes et al. (2014) have identified the Bulldog Shale as a potential source of quartzite, quartz, chert, and silcrete.

During the Tertiary period, the Bulldog Shale endured a prolonged period of deep weathering. Silica-rich groundwater movement at this time contributed to the formation of silcrete layers in the weathered profiles of the Bulldog Shale (Wopfner, 1978). Silcrete-capped plateaux formed widely throughout the far north of South Australia during the Tertiary Period. Although such plateaux are not in the DSC study area, it is worth noting that extensive Tertiary-age silcrete formations (e.g., Cordillo Silcrete) occur immediately west and southwest of the study area (Krieg, 1985), where Ludbrook (1980, p. 100) has noted that the silcrete capping of the Emery Range weathers into the surrounding gibber plain as “pebbles or boulders of chalcedony or other very hard forms of silica.”

The Quaternary geological record is characterized by the formation of extensive Pleistocene surface gravels and episodes of spring related alluvial deposition (Figure 4-1d). As Tertiary silcretes progressively broke up and eroded away, the retreating escarpments shed detrital silcrete gravels that succumbed to further weathering and redeposition in the study area via surface sheetwash and gibber formation processes (Krieg, 1985, pp. 32–33).

At lower elevations in the DSC study area, travertine and clay deposits associated with the mound spring complex are aggraded, including the Dalhousie Formation, a Pleistocene-age smectite rich carbonate/clay deposit indicative of an ancient spring-fed lakebed that once occupied the central study area (Krieg, 1985, p. 36). Elsewhere, Pleistocene and Holocene-age alluvial deposits accumulated along the drainages, channels, and floodplains associated with the spring complex and water dissected features in the landscape (Figure 4-1d).

4.3.3 Mineralogical and Spectral Properties of Silcrete

Eggleton (2001, p. 108) defines silcrete as “strongly silicified, indurated regolith, generally of low permeability, commonly having a conchoidal fracture with a vitreous luster.” Silcrete forms through a process that involves the dissolution and mobilisation of water-soluble silica through deeply weathered, unconsolidated sediment. The silica-rich aqueous solution infiltrates the cracks and pores of the

underlying regolith and, over time, the silica precipitates and cements the clastic rock matrix. Depending on the geological properties of the parent regolith, silcrete can exhibit a wide range of colour and mineralogical variation due to parent material clasts (e.g., sediments, saprolite, or soil), which largely include detrital quartz grains cemented with deposits of secondary silica (Hughes et al., 2014; Milnes & Thiry, 1992). The SiO₂ content of silcrete normally exceeds 95% (Hughes et al., 2014; Summerfield, 1983), but it no less than 85% SiO₂ by weight (Summerfield, 1983). Hughes et al. (2014, p. 113) note that it is not unusual for some central Australian silcretes to contain 98% silica. Petrological studies indicate that the silcrete matrix contains a variable mix of amorphous, cryptocrystalline, and microcrystalline forms of silica, and granular or fibrous crystalline microstructures may be present (Hughes et al., 2014; Thiry & Milnes, 2017). It has also be noted that opal, chalcedony, and microquartz are common components of silica cements (Butts, 2014; Wopfner, 1978), an observation which is evident in many studies of Australian silcretes (Hughes et al., 2014; Milnes & Thiry, 1992; Taylor & Eggleton, 2017; Thiry & Milnes, 2017; Wopfner, 1978).

Central Australian silcretes are typically gray or brown in colour, but other variations are possible (Hughes et al., 2014). The precise manner in which silcrete forms is somewhat enigmatic (see Taylor & Eggleton, 2017), but our review indicates that silcrete can form in a number of geological contexts and it fundamentally involves the natural percolation and/or lateral movement of silica-rich solutions through weathered sediment (see Simon-Coincon, Milnes et al., 1996; Taylor & Eggleton, 2017; Thiry & Milnes, 1991; Thiry & Milnes, 2017; Thiry et al., 2014; Thiry et al. 2006; Wopfner, 1978). Silica is released into the geological environment through continental weathering, hydrothermal activity, and biogenic precipitation. SiO₂ becomes water-soluble under particular pH and temperature conditions and, once dissolved, the aqueous solution permeates and infills the cracks and pores of the deeply weathered regolith profile. As the solution dehydrates, the silica precipitates and indurates the clastic regolith matrix (Figure 4-3a). It is not uncommon for silcrete duricrusts to form on the upper profile of ancient weathered sediments (e.g., “pedogenic silcrete”) (Alley, 1998; Thiry & Milnes, 2017; Thiry et al., 2014) (Figure 4-3b); however, it can also form via phreatic conditions near the water table (e.g., “groundwater silcrete”), so localized subsurface epigenetic silcrete formations occur as well (Alley, 1998; Thiry & Milnes, 1991; Thiry & Milnes, 2017;

Ulyott & Nash, 2016). Because silcrete is a resilient material, weathered silcrete pebbles and cobbles are common on the gibber surface (Figure 4-3c).

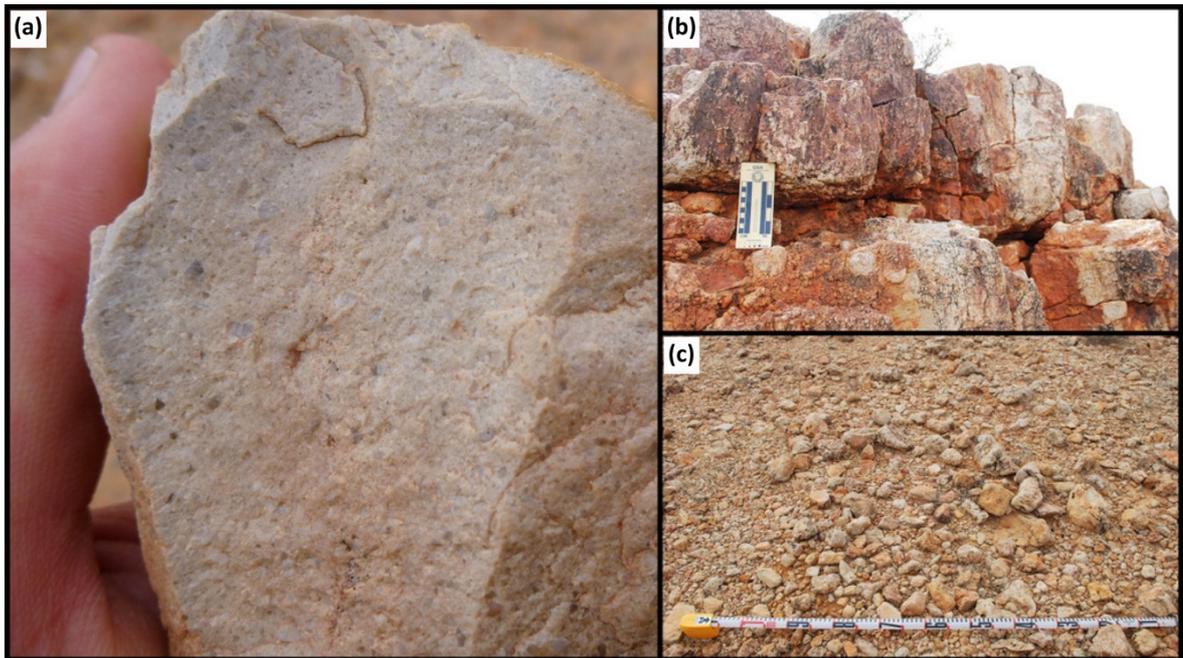


Figure 4-3 Examples of silcrete in the vicinity of the project area. (a) Macro photography of the silcrete matrix showing detrital macroquartz clasts of parent rock tightly cemented by secondary microscopic silica (i.e., forms of hydrated silica). (b) Columnar silcrete duricrusts capping atop of mesa in Emery Range. (c) Weathered silcrete lag gravels form the stony pavement that “armors” the gibber plain surface. A colour version of this figure is available in the online PDF

The term “hydrated silica” is used in remote sensing studies to describe a spectral family of quartz minerals comprised of amorphous, cryptocrystalline, and microcrystalline forms of SiO_2 , with molecular water and/or hydroxyl (silanol) either structurally bound or adsorbed on their crystalline surface (Flörke et al., 1991; Graetsch et al., 1985; Smith et al., 2013). The hydrated silicate minerals of interest to this study include opal, chalcedony, agate, and microquartz (Ehlmann et al., 2009; Milliken et al., 2008; Smith & Bandfield, 2012; Smith et al., 2013). Opal is weakly crystalline, comprised of amorphous silica with no crystalline organisation (Graetsch et al., 1985; Thiry et al., 2014). Chalcedony and agate (a variety of chalcedony) are cryptocrystalline to microcrystalline forms of silica with microfibrillar crystalline structures (Graetsch et al., 1985; Leudtke, 1992). Microquartz refers to a granular microcrystalline variety of quartz composed of silica grains $<20 \mu\text{m}$ (Flörke et al., 1991; Smith et al., 2013). Of importance when using “hydrated silica” terminology, Smith et al. (2013, p. 634) point out that macrocrystalline quartz is not hydrated silica because it has a very regular crystalline structure that lacks the void spaces and defects needed to allow for water or hydroxyl features.

When “hydrated silica” is used throughout this article, it does not imply molecular water (H_2O) is in the chemical formula of the silicate mineral, although it is possible. For example, only opal ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) is geochemically denoted as hydrated, but chalcedony, agate, and microquartz (all SiO_2) are also considered hydrated for remote sensing purposes due to trace molecular water trapped in their crystalline structure and hydroxyl groups on silica surfaces (see Flörke et al., 1991; Flörke, Köhler-Herbertz, Langer, & Tönges, 1982; Graetsch et al., 1985; Smith et al., 2013). Evidence of their aqueous past is preserved in their crystalline structure, which can be measured with a spectroradiometer to demonstrate the molecular presence of interstitial water and/or hydroxyl (OH-) adsorbed on silica surfaces (Flörke et al., 1991). The hydroxyl bond creates a broad spectral absorption feature at 2.21–2.26 μm that is diagnostic of this family of hydrated silicate minerals. Research shows that various forms of hydrated silica, as described above, may be present in the cemented silcrete matrix (Hughes et al., 2014; Taylor & Eggleton, 2017; Thiry & Milnes, 2017; Wopfner, 1978). Thus, it would seem that the spectral characteristics of hydrated silica mineralogy should be useful for mapping silcrete and related silicified rocks.

Opal, agate, chalcedony, and microquartz share common diagnostic spectral features that are indicative of their hydrated silica mineralogy. To illustrate this similarity, we compared opal, agate, and chalcedony using spectra measured by the United States Geological Survey (USGS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the University of Adelaide Spectroscopy Laboratory (UniA) (see Smith et al. (2013, p. 637) for spectral comparison of microquartz). Figure 4-4 illustrates the spectral reflectance values of these materials in the 1.2–2.4 μm SWIR spectrum. Opal, agate, and chalcedony have three pronounced absorption features (F) centering around 1.40–1.46 μm (F1), 1.91–1.96 μm (F2), and 2.21–2.26 μm (F3) (Figure 4-4). Together, these features positively identify each material as a hydrated silicate mineral. The absorption features formed at these locations are a consequence of the interaction of electromagnetic radiation and molecular composition of the material, and in this case, the features indicate the involvement of water with the mineral formation (Chauviré et al., 2017). For instance, the absorption feature spanning 1.41–1.46 μm is a vibrational overtone of the hydroxyl (OH—1.41 μm) and water (H_2O —1.46 μm) molecules associated with SiO_2 mineralisation (Chauviré et al., 2017; Christy, 2010, 2011; Kokaly et al., 2017; Livo et al., 2007). Similarly, between 1.91 and 1.96 μm ,

there is an absorption feature related to molecular water adsorption and bonding on the crystalline surface (Chauviré et al., 2017; Graetsch et al., 1985). The presence of features at 1.41–1.46 μm and 1.91–1.96 μm are common to many hydrated minerals, so these two features are not considered exclusively diagnostic of hydrated silica. However, in conjunction with the broad “u-shaped” absorption feature observed between 2.21 and 2.26 μm , the combination of these three features is highly distinctive of hydrated silica mineralisation (Ehlmann et al., 2009; Kokaly et al., 2017; Milliken et al., 2008). The broad feature at 2.21–2.26 μm (Figure 4-4) is the result of silanol (Si-OH) bonding on the surface of the crystalline structure, and it is a tell-tale marker for opal, agate, chalcedony, and microquartz (Ehlmann et al., 2009; Flörke et al., 1991; Livo et al., 2007; Milliken et al., 2008; Smith et al., 2013).

Much of the SiO_2 composition of silcrete derives from the cementation of secondary hydrated silica. Since silcrete is a hydrated silica-bearing rock, it is likely that it shares similar spectral properties with agate, chalcedony, opal, and microquartz. This hypothesis will be tested by our research but there is existing evidence that suggests rocks rich with hydrated silica will also have a broad silanol absorption feature at 2.21–2.26 μm . This phenomenon has been documented in the case of “opalized tuff” where the secondary mobilisation of hydrated silica has resulted in the silicification of unconsolidated volcanic ash (Evernden & Kistler, 1970, p. 11). Like opal, agate, and chalcedony, opalized tuff exhibits a broad absorption feature at 2.21–2.26 μm (see Kokaly et al., 2017; Swayze, 1997). Thus, based on this rationale, the spectral signature of hydrated silica should be pronounced in a similarly silicified rock like silcrete.

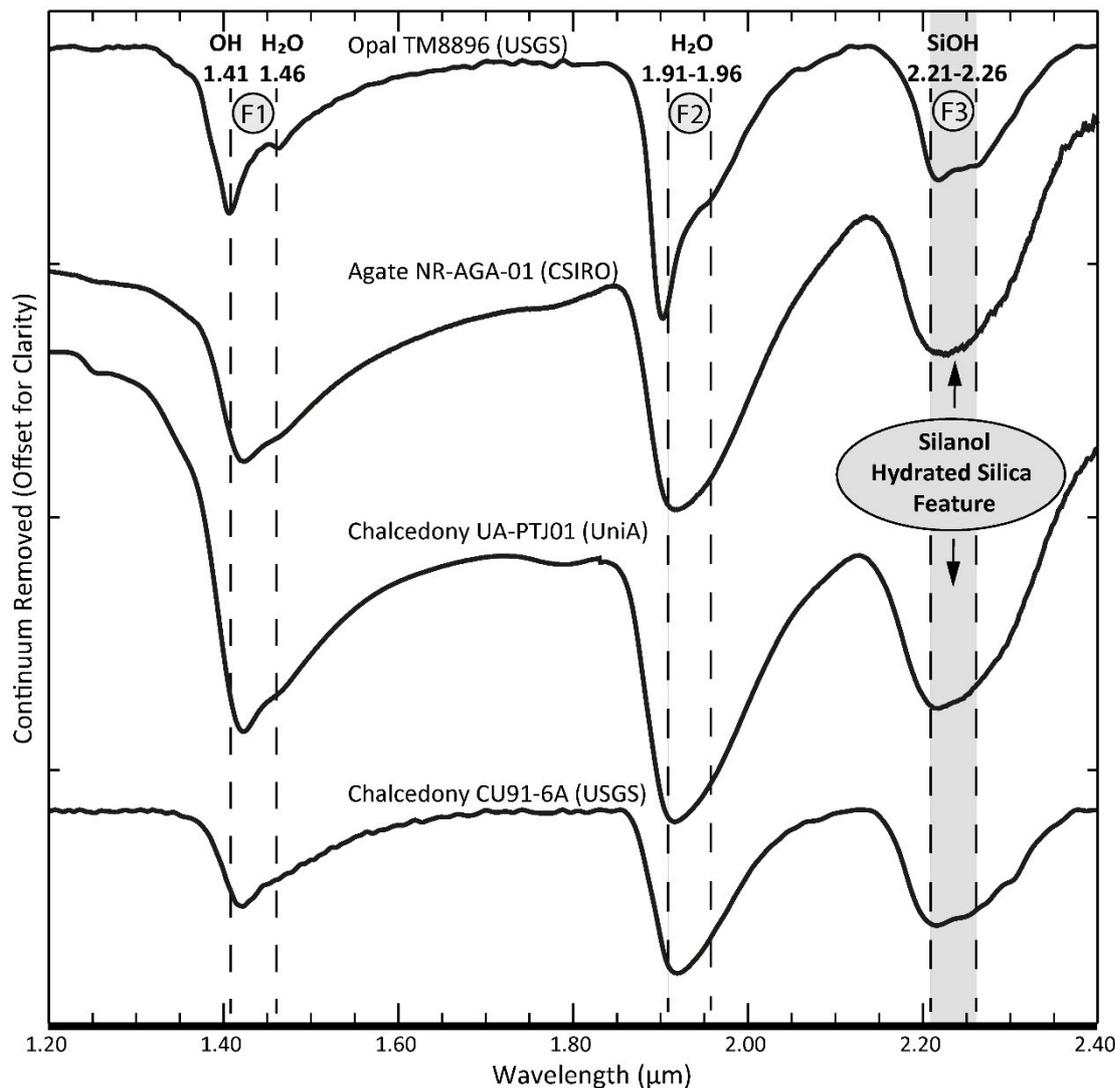


Figure 4-4 Spectral reflectance curves of opal, agate, and chalcedony in the SWIR spectrum. Collectively three molecular absorption features at approx. 1.41 μm (F1), 1.91 μm (F2), and 2.21–2.26 μm (F3) positively identify this family of SiO_2 minerals. The broad absorption feature 2.21–2.26 μm (shaded gray for emphasis) is diagnostic of hydrated silica mineralisation. Sample codes and spectral laboratory noted in the illustration. SWIR, shortwave infrared.

4.3.4 Archaeological Relevance of Silcrete

Stone artefacts manufactured from silcrete and related silicified rock have been documented by many historic and contemporary researchers of central Australian Aboriginal anthropology and archaeology (Davies et al., 2018; Douglass et al., 2016; Douglass et al., 2017; Gould & Saggars, 1985; Gould, 1977, 1978; Gould et al., 1971; Graham & Thorley, 1996; Horne & Aiston, 1924; Howchin, 1934; Hughes & Lampert, 1985; Hughes et al., 2011; Hughes et al., 2014; Lampert, 1985, 1989; Law, 2009; Sullivan et al., 2014). Collectively, this previous work indicates that silcrete was an economically important raw material for Aboriginal groups; thus it is not surprising that silcrete is often recognized as the most common raw material used for stone artefact manufacture in central Australian archaeological sites

(Davies et al., 2018; Douglass et al., 2017; Hughes et al., 2014; Lampert, 1985) (Figure 4-5).

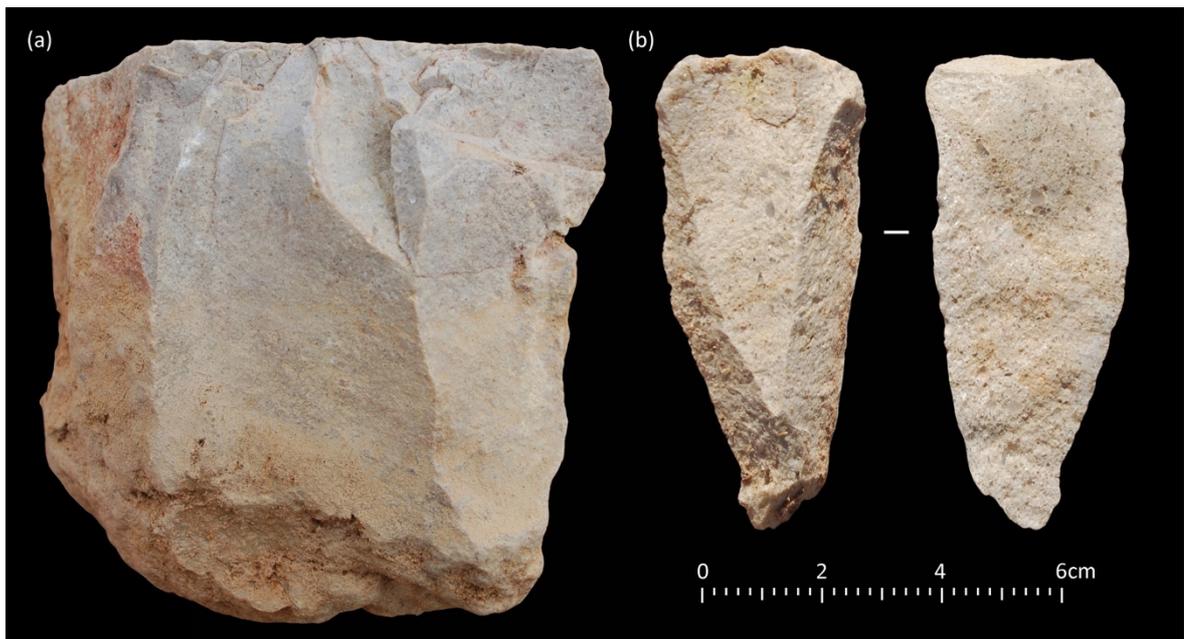


Figure 4-5 Silcrete artefacts often occur in high frequencies in central Australian assemblages. Pictured above are an example of a silcrete (a) core and (b) flake.

The use of silicified rocks for stone tool manufacture is documented in the early anthropological research of Spencer and Gillen (Spencer, 1896; Spencer & Gillen, 1904). Historically described as “opaline quartzite,” Spencer and Gillen document the importance of this silicified material in the manufacture of resin hafted knives (Spencer & Gillen, 1904, p. 644) and stone “chisels” (Spencer, 1896, p. 13). Horne and Aiston (1924) 17 also noted the frequent use of “chalcedony” to produce “tuhla” adzes in the Lake Eyre Basin, observing that tulas manufactured from chalcedony were not only used for woodworking activities, the raw material also had mythological importance to the Aboriginal people of northeast South Australia (Horne & Aiston, 1924, p. 127).

Ethnoarchaeological research further emphasizes the importance of silcrete and chalcedony as a natural resource for Aboriginal people. Traditional knowledge and usage of quarry sites continued into the middle of the late twentieth century amongst some community elders. Several archaeologists working in remote areas of the central and western desert regions of Australia were led to “chalcedony” stone artefact quarries by Aboriginal informants (Gould et al., 1971; Graham & Thorley, 1996; Hayden, 1979; Law, 2009; Tindale, 1965). Surface artefact frequencies and informant accounts suggest that quarry sites were revisited over time, by multiple generations, perhaps for hundreds or thousands of years.

Contemporary archaeological research has continued to recognize the importance of silcrete as a prehistoric commodity. A silcrete quarry investigated in central Australia by Sullivan et al. (2014) highlights how silcrete was specifically targeted and “mined” for raw materials. Research by Douglass and Holdaway (2011), Douglass et al. (2016) and Douglass et al. (2017) further acknowledges the important contribution of silcrete to the Aboriginal economy, recording it as the dominant raw material used for artefact manufacture at sites they investigated on the southeast fringe of central Australia.

4.4 MATERIALS AND METHODS

4.4.1 Laboratory Spectroscopy

Spectral reflectance measurements of collected rock and mineral field samples were conducted by WBL at the University of Adelaide Spectroscopy Lab. The original provenance of these samples is shown in Figure 4-1b. An ASD FieldSpec® 3 spectroradiometer was used to measure spectral reflectance on the DSC samples and additional central Australian rock specimens, where available. In some instances, the spectral reflectance data were further supplemented with sources stored in reputable spectral libraries maintained by CSIRO (<https://mineralspectrallibraries.csiro.au>) and the USGS (<https://crustal.usgs.gov/speclab/QueryAllo7a.php>) (see Figure 4-4).

The FieldSpec® 3 was used to record electromagnetic reflectance for 2151 narrow bands, between 0.35 μm and 2.50 μm , in each spectral measurement. The spectroradiometer measures each band at an interval of 0.0014 μm along with the spectral range 0.35–1.00 μm . Between 1.0 and 2.5 μm , an interval of 0.0020 μm was consistently measured. The reflectance spectra of each sample were collected in dark-room lab conditions, in accordance with methodological standards published by ASD (2010).

4.4.2 Hyperspectral Image Analysis

The hyperspectral imagery utilized in this study is a HyMap™ product, acquired for the Dalhousie Springs area in March 2009 as part of a National Water Commission study (Lewis et al., 2013). The image was acquired at the end of a long and dry summer to ensure maximum bare-earth observations and minimal interference from vegetation growth. The image is a mosaic of airborne image strips, preprocessed by HyVista Corporation and delivered as an apparent surface reflectance hyperspectral data set, georegistered to the World Geodetic System 1984

(WGS84) datum (but reprojected to Geocentric Datum of Australia 1994 (GDA94) MGA Zone 53 J). The HyMap image has a high spatial and spectral resolution, with a pixel size of 3.1 m and 126 narrow spectral bands spanning the wavelength range of 0.45–2.5 μm and bandwidths between 0.015–0.020 μm . Collectively, the layer stack (or datacube) constitutes a detailed spectrum for each image pixel, thereby enabling each individual pixel to be visually or mathematically analyzed for mineral identification (see Figure 4-4).

Image analysis was done using Environment for Visualizing Images (ENVI®) software version 5.3 (Exelis Visual Information Solutions, Boulder, Colorado). Using the spectral feature fitting (SFF) algorithm developed by Clark, Gallagher, and Swayze (1990), the spectral signature of chalcedony (UA-PTJ01) was selected as the reference mineral spectrum for targeting and discriminating hydrated silica mineralisation in the hyperspectral image. SFF processing was isolated to SWIR image bands 103-120 (2.10–2.39 μm), as this is the spectrum that encompasses the broad silanol absorption feature (2.21–2.26 μm) recognized as being diagnostic of hydrated silica mineralisation (Ehlmann et al., 2009; Livo et al., 2007; Milliken et al., 2008). Moreover, as our research suggests, this absorption feature should be indicative silica-rich knappable stone-like silcrete.

In processing the hyperspectral image, the SFF algorithm compared the lab reference spectrum with the image pixel spectra by normalizing spectral reflectance values to a common scale, an automated process referred to as “continuum removal.” The SFF algorithm then used a least-squares technique to match the spectral shape of the hydrated silica absorption feature with the HyMap™ pixel spectra.

The SFF algorithm generates two continuous rasters—1.) a “scale” image and 2.) a “root mean square” (RMS) image. A ratio of the “scale” image and “root mean square” image (i.e., scale/RMS) produced a “goodness-of-fit” raster, where image pixels with higher values are suggestive of areas where the reference spectra closely matches the dominant geological material occupying the ground surface. Thus, the higher pixel values are more likely to have rocks or minerals rich with hydrated silica mineralisation.

4.4.3 Post Hoc Corroboration with Multispectral Imagery and Fieldwork

The findings of our hyperspectral mapping study were corroborated with the post hoc support of a complementary multispectral image product and fieldwork. We compared the distribution of hydrated silica mineralisation in the processed HyMap image with the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Silica Index map of Australia, published by CSIRO on their Data Access Portal (<https://doi.org/10.4225/08/51400D6F7B335>) (Cudahy, 2012). The CSIRO “Silica Index” map is georeferenced to the WGS84 coordinate system but reprojected to GDA94 MGA Zone 53J for this study. It is a free digital data product created using emissive thermal imagery acquired by the Japanese space agency's ASTER multispectral imaging instrument, onboard NASA's Terra satellite. The ASTER device measures electromagnetic surface radiance in 14 multispectral bands, including emissive thermal infrared (TIR) wavelengths (8.1–11.7 μm). These thermal bands may be used to identify the characteristic emissivity spectrum of quartz-bearing sediments and silica-rich rock. Employing a methodology utilized by Cudahy et al. (2002) and Hewson et al. (2005), the ASTER Silica Index product uses the TIR band ratio $\text{TIR_Band13}/\text{TIR_Band10}$ ((10.250–10.950 μm)/(8.125–8.475 μm)) to discriminate SiO_2 -rich rocks and minerals, including quartzite, silcrete, and silica-rich colluvial/alluvial gravels (Cudahy, 2012, p. 23). Although the ASTER image has coarser resolution (90 m pixel), it is useful for corroborating our hyperspectral results as it provides an independent post hoc reference map to substantiate our hydrated silica mineralisation map.

Our hyperspectral analysis was further supported with field observations and spectroscopic data. The objective of fieldwork was two-fold. The first was to critically assess if hyperspectral mapping results successfully discriminated hydrated silica-bearing rocks. The second purpose of fieldwork was to collect geological samples for laboratory spectroscopy. This involved the collection of archetypical specimens of major geological formations, as well as samples of silcrete at random locations across the project area (Figure 4-1b). Collected rock samples were approximately 5 cm in size.

Fieldwork was completed 24–28 October 2018 by WBL and a field assistant. The fieldwork involved hiking across and observing major geological formations, as well as inspecting areas mapped as having hydrated silica-bearing rock. A handheld Garmin GPSmap 64S was used to acquire a waypoint for each collected field

specimen (see Figure 4-1b). At each location, notes were collected on surface visibility, landform, geological context, and materials present. Photographs of the general landscape and materials of interest were taken, as appropriate and rock samples were bagged and labeled before transport to the University of Adelaide spectroscopy lab for further analysis.

4.5 RESULTS

The SFF methodology produced a continuous raster map showing the distribution of hydrated silica mineralogy for the DSC study area (Figure 4-6a). This map, described hereon as the “Hydrated Silica” map, shows areas where the chalcedony reference spectra most closely match the pixel spectra of the hyperspectral image over the wavelengths 2.10–2.39 μm , which span the hydrated silica absorption feature. High goodness-of-fit pixel values are interpreted as places where hydrated silica-bearing rocks dominate the ground surface. The Hydrated Silica image shows that high-value pixels group strongly along the edge of the gibber plain that surrounds the central Dalhousie anticline, forming a roughly oval or crescent-like shape around the topographically lower alluvial deposits of the study area. Thus, as the map suggests, rocks rich with hydrated silica mineralisation occur in greater abundance on the stony plain than in the central anticline depression.

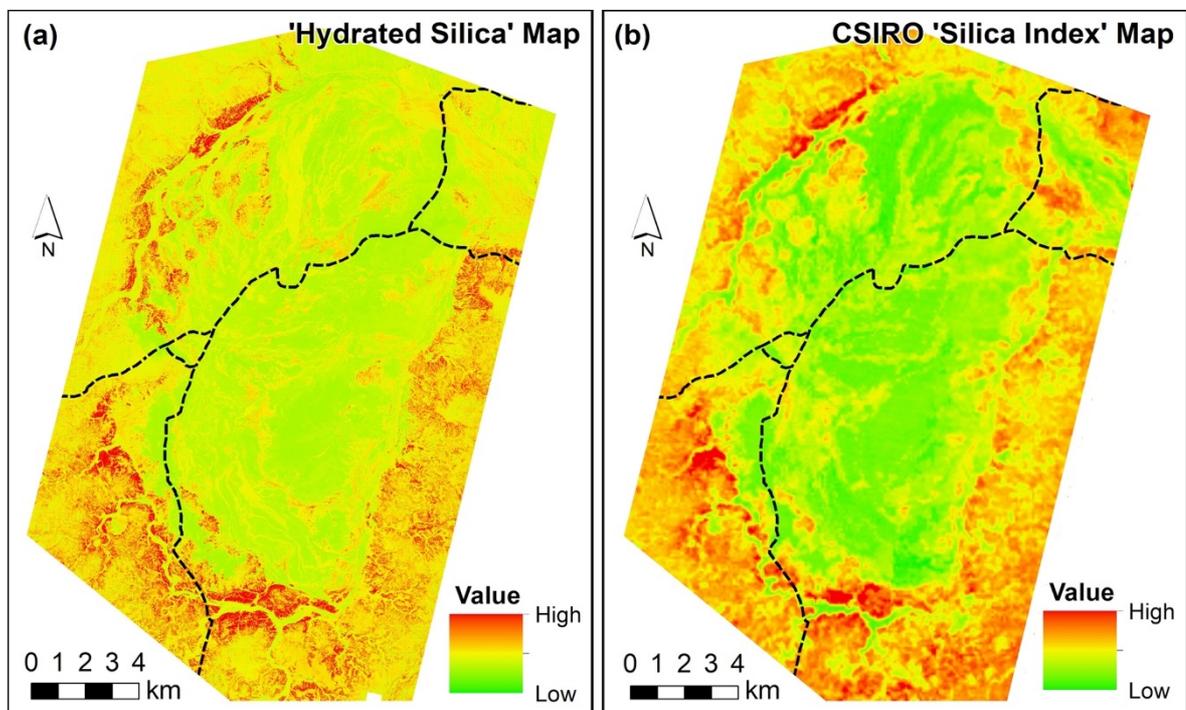


Figure 4-6 (a) Hydrated Silica map generated by matching chalcedony lab reference spectra (UA-PTJ01) and HyMap SWIR bands 2.1–2.39 μm with the SFF algorithm. (b) CSIRO Silica Index map created from ASTER TIR band ratio (b13/b10) (Cudahy, 2012). Both raster images are stretched at 2.5 standard deviations of the mean image pixel value. CSIRO, Commonwealth Scientific and Industrial Research Organisation; SFF, spectral feature fitting; SWIR, shortwave infrared.

The distribution and relative abundance of the hydrated silica mineralisation is echoed in CSIRO's Silica Index product, depicted in Figure 4-6b. Like the Hydrated Silica map, the CSIRO Silica Index map shows a similar distributional pattern for silica-rich geological materials along the edge of the Dalhousie anticline, albeit at a much coarser image resolution. Although the spatial resolution of the HyMap hyperspectral image (3.1 m) and ASTER TIR image (90 m) are considerably different, there are strong parallels in the mineralogical patterning depicted in each image. High pixel values of siliceous mineralisation are evident in the northwest, southwest, southeast, and eastern anticline area. The area of greatest disagreement between the images is in the northeast DSC study area, where the CSIRO Silica Indexmap shows an abundant distribution of silica-rich rocks in the alluvial outflows of Dalhousie anticline. In contrast, the SFF values in our Hydrated Silica image suggests there is a diminished abundance of hydrated silica in the drainages of the northeast.

Field observations confirmed that silcrete is the principal raw material discriminated in both images. Silcrete lag gravels are the most abundant material on the surface of the gibber plain surrounding the study area (Figure 4-2) and the central DSC is covered in fine alluvial sediments, lacking any surface rock outcrops. The stony plain, on the other hand, is extensive and largely devoid of vegetation. Silcrete-capped mesas, mapped as Cordillo silcrete, occur immediately west and southwest of the DSC study area but fieldwork efforts were unsuccessful in locating any *in situ* silcrete duricrusts in the immediate study area.

Silcrete lag gravels drape across the surface of several mapped geological formations (e.g., Bulldog Shale, Oodnadatta Formation, and Pleistocene Gravels), which are visually indistinguishable from one another in most cases. Near the upper edge of the anticline, silcrete gravels are densely packed and cover the underlying soil matrix. Further away, but still on the surface of the stony plain, surface patches of soils intermix with the silcrete lag gravels. The fine sediment in these areas is predominantly clay, which contributes to the heave process involved with the formation of the desert pavement (Dixon, 2009, p. 115).

Our laboratory spectroscopic results show there is a strong hydrated silica spectral feature in the silcrete samples collected in the DSC study area (Figure 4-7). In all instances, the silcrete spectra closely match the lab reference spectra of

chalcedony, suggesting that chalcedony or similar hydrated silicate minerals (e.g., opal, agate, and microquartz) are present in the silcrete matrix.

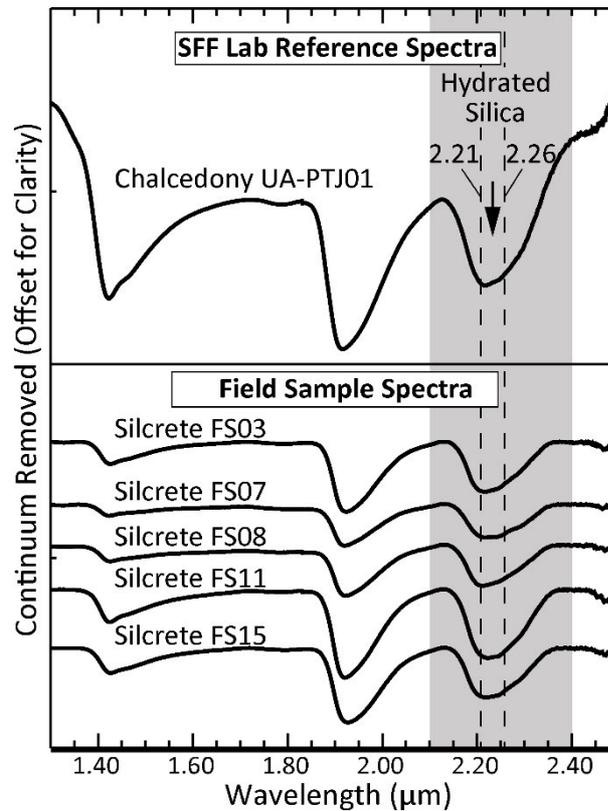


Figure 4-7 The spectral curves for specimens of major geological formations vs silcrete specimens show that the prominent hydrated silica feature is exclusive to silcrete. The gray area denotes the range of the SWIR spectrum isolated for SFF analysis. SFF, spectral feature fitting; SWIR, shortwave infrared.

4.6 DISCUSSION

This study highlights the benefit of using advanced remote sensing technologies to map potential sources of “tool-stone.” As far as we are aware, hyperspectral remote sensing has not been utilized by archaeologists to map silcrete, so this study is possibly the first of its kind in Australia. We have shown that hydrated silica absorbs radiant solar energy in a distinctive and unique manner in the SWIR spectrum, enabling silcrete to be detected in the HyMap image.

Archaeological interest in silcrete as a lithic resource for stone tool production has increased substantially over the past two decades, both in Australia and internationally (see Wragg Sykes & Will, 2017). Silcrettes occur over extensive areas of central Australia and they are abundant in many arid and semiarid landscapes around world. Thus, in this regard, many arid environments may be well-suited for hyperspectral mapping of silicified “tool-stone” sources. However, we highlight that this study has benefited from it being in a sparsely-vegetated terrain, with

considerable stone and soil exposure. It is unlikely that this approach would be successful in nonarid landscapes, where dense surface vegetation obscures bare-earth observations.

The manner in which we applied the SFF algorithm was effective in matching the library reference spectra to the hyperspectral image spectra. This is partly because the SFF algorithm is sensitive to matching the subtle silanol absorption feature of hydrated silica. However, in applying the SFF algorithm, or other similar spectral matching algorithms, it is equally important to select the appropriate spectral range for the analysis. The wavelength range isolated for this analysis is based on the shape of the diagnostic absorption feature for hydrated silica, which in this case, spans the SWIR 2.10–2.39 μm range. These bands encompass the entire shape of the silanol absorption feature for hydrated silica, thereby enabling the SFF algorithm to effectively match the reference spectra with pixel spectra in the hyperspectral image. The result shows that silcrete gravels are relatively abundant and widely distributed across the gibber plain.

The distribution of the silcrete lag gravels in our Hydrated Silica map is similar to the CSIRO Silica Index map prepared by Cudahy (2012). Although the CSIRO index is based on emissive thermal satellite imagery, there are parallels in the distribution of silcrete mapped from the hyperspectral and TIR images. In both maps, silcretes are distributed around the periphery of the central “core” of the Dalhousie anticline, primarily on the surface of the gibber plain. Few patches of silicified rock are mapped in the lower alluvial areas of the DSC study area itself. There is strong similarity between the distribution and abundance of silica in both the images, and it shows there is good corroboration between independent datasets, even though they measure quartz silica mineralisation differently.

The area of greatest disagreement between the Hydrated Silica mineralisation map and the CSIRO Silica Index map is in the northeast alluvial lowlands. We suggest the disparity could be due to a number of possibilities. The Hydrated Silica map emphasizes silicified rocks (e.g., silcrete) whereas the Silica Index map highlights a greater range of siliceous rocks and sediments, which may include silcrete, quartzite, sandstone, and other rocks or sediments containing macroquartz. As pointed out by Cudahy (2012, p. 23) the silica index can result in high values in alluvial contexts due to the abundance of clean, coarse quartz grains ($>250 \mu\text{m}$). Research by Livo et al. (2007, p. 495) and Smith et al. (2013, p. 634) have also pointed out that macrocrystalline quartz does not have a hydrated silica absorption

feature in the SWIR region, which may explain why the siliceous alluvium is not highlighted in the hyperspectral imagery. It is also possible that moisture in the alluvial sediments has affected the emissivity signal in the thermal imagery. The difference may also be explained by the spectral mixing of creek alluvium and siliceous gravels, which could have affected the purity of the reflectance and emissivity pixel measurements for each respective image. Future investigations will need to explore the minor disparity between the images more thoroughly, but for the moment, the similar distribution of silcrete lag gravels is obvious between the two images (Figure 4-6).

Our discrimination of hydrated silica in the hyperspectral image is further supported by the spectroscopic analysis of the collected field specimens. The laboratory spectroscopy of the silcrete field samples shows that the hydrated silica is present in all specimens (Figure 4-7). No other major geological formations in the DSC study area share similar spectral characteristics with silcrete (Figure 4-8), illustrating the effectiveness of the SFF algorithm in matching the reference spectra to the target spectra recorded in the HyMap image.

Because silcrete forms in various contexts where weathered regolith becomes indurated and cemented by secondary silica, it can potentially occur in multiple geological formations. Therefore, we suggest that the Hydrated Silica map is useful to researchers interested in locating where silcrete (or similarly silicified rocks) formed in the landscape, regardless of surface geology maps or terrain attributes. If our research had relied solely on mapped geological formations for this case study, we would have been misguided as to how widespread the distribution of silcrete is in the landscape. Moreover, if we targeted terrain features like mesas to locate *in situ* silcrete duricrusts, our investigations would have been misguided, as none of the mesas we observed in the DSC study area are capped with silicified material.

Although the Hydrated Silica map may be more useful for locating silicified raw materials than conventional geological maps, it does not pinpoint particular archaeological site types such as quarries or stone artefact scatters. Despite the high spatial resolution of the HyMap imagery, it is unlikely that quarried localities or large knapping areas can be discriminated from the background lithology due to the abundance of silcrete on the gibber plain. We suggest the Hydrated Silica map is more appropriately viewed as a site suitability model, and in conjunction with other spatial data (e.g., water sources, drainages, slope, aspect, topographic position

index), the hydrated silica mineralisation data are useful for discriminating locations with suitable conditions for particular site phenomena to occur.

In addition to custom geological mapping, possibly the greatest benefit of this research lies in its potential to save researchers time and money by using digital analysis to rapidly identify natural landscape patterns and target areas of interest behind a computer desktop, without the need for costly and time-consuming field reconnaissance. Custom-made hyperspectral imagery can cost thousands of dollars, but free or low-cost hyperspectral imagery is becoming increasingly available via government agencies and private enterprise. Hyperspectral imagery from the NASA Hyperion satellite is freely available from a number of online portals, and HyVista Corporation maintain an archive of previously flown HyMap imagery that can be purchased for many areas of Australia. New hyperspectral instruments from Germany (EnMap) and NASA (HypIRI) are in development, with satellite launches planned in the next 5–10 years. These projects will increase the accessibility and global coverage area of hyperspectral imagery, which offers promise to the next era of remote sensing for archaeological research.

In addition, we have highlighted that CSIRO has made its silica index TIR product free to download, and it offers continental-wide coverage of Australia (Cudahy, 2012). The TIR resolution is much coarser than the HyMap product but it has the advantages of being a preprocessed raster file, so end-users can readily download and view the imagery in any GIS software package. The TIR imagery discriminates silica in unconsolidated sediments and siliceous rocks (e.g., sandstone, quartzite, and silcrete), so it does not exclusively identify hydrated-silica-bearing rock. Thus, there are constraints on the usefulness and validity of the imagery. However, in the right environmental context (e.g., arid or semiarid landscapes with abundant bare-earth observations), the silica index product may be useful for discriminating siliceous rock sources, but the GIS technician may need to mask image pixels where colluvial/alluvial sediments, quartz sands, or terrain types interfere with the interpretation of some silica index values.

In closing, this project has illustrated how aerial and satellite remote sensing image products can assist archaeological researchers with identifying where siliceous rock lithologies occur. Remote sensing information, as illustrated here, has the potential to assist investigators with determining where specific archaeological site types (e.g., quarries, lithic scatters, or habitation sites) are likely to be found. This information may also be useful to proximity analyses, providing researchers

with a more accurate spatial dimension to investigate how stone artefacts were utilized and transformed based on their proximity to resources in the landscape.

4.7 CONCLUSIONS

This study demonstrates the usefulness of aerial hyperspectral imagery for mapping sources of silicified raw materials that may have been targeted for stone artefact manufacture by past Aboriginal peoples. Research has shown that hydrated silica-bearing rocks exhibit a diagnostic absorption feature in the SWIR spectrum, centering around 2.21–2.26 μm . Using a spectral matching algorithm known as SFF, we matched this absorption feature to pixel spectra in a HyMap hyperspectral image to show the distribution of hydrated silica mineralisation for the Dalhousie Springs area of central Australia.

Subsequent field investigations confirmed the mapped material is silcrete, a rock widely used for stone artefact manufacture in central Australia. Laboratory spectroscopy of the silcrete field samples supports the findings of hyperspectral image analysis, showing that the spectral absorption feature for hydrated silica mineralisation is present in all collected specimens. Moreover, ASTER thermal satellite imagery processed by CSIRO shows a similar pattern in the distribution of silica-rich rock in the DSC study area, supporting our HyMap image analysis. Thus, the thermal CSIRO image product may also be useful to Australian archaeologists interested in mapping silcrete and other siliceous rock resources.

Although our study is based in central Australia, the applicability of this work is wide-ranging. The advanced remote sensing methodologies and rationale we offer here can potentially assist desert archaeologists grappling with similar lithic resource mapping questions in other arid regions of the world. Access to such regions is often limited by distance, geography, and research budgets. As the availability of hyperspectral SWIR and multispectral TIR imagery increases in the future, we believe that archaeologists will progressively see the benefit in utilizing the advanced remote sensing methods espoused in this article.

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4.9 CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

4.10 DATA AVAILABILITY STATEMENT

The HyMap data that support the findings of this study are stored at the University of Adelaide, School of Biological Sciences. Restrictions apply to the availability of these data, which were used under license for this study. Research data are not shared, but reasonable requests to the corresponding author may be considered, subject to consultation and licensing agreements with project stakeholders. All additional spatial data used in this article are freely available online, as cited elsewhere.

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Contribution to the Paper	W.B.L. conceived the idea for this research. He is the principal author, creator, and spatial science technician behind this study. He drafted the original version of the paper and created all of the figures in the paper. Through collaboration with his co-authors, integrated their comments, contributions and edits into the final document.			
Overall percentage (%)	85%			
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.			
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By signing the Statement of Authorship, each author certifies that:

- i. the candidate's stated contribution to the publication is accurate (as detailed above);
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Signature	<table border="1" style="width: 100%;"> <tr> <td style="width: 80%;"></td> <td style="width: 20%;">Date</td> <td>25/03/2020</td> </tr> </table>		Date	25/03/2020
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Chapter 5 Using Satellite Imagery to Evaluate Precontact Aboriginal Foraging Habitats in the Australian Western Desert

5.1 ABSTRACT

Australian Aboriginal peoples have occupied the continent's Western Desert region for millennia, yet there has been little modelling of the land use that underpinned human occupation for so many areas. Here, we investigate the dynamics of historic and precontact desert land use using Earth observation data to identify the distribution of suitable foraging habitats. Suitability was modelled in an ideal environmental scenario, based on satellite observations of water abundance, vegetation greenness, and terrain ruggedness. Our model shows that highest-ranked foraging habitats do not align with land systems or bioregions that have been used in previous reconstructions of Australian prehistory. Our model identifies impoverished areas where unsuitable foraging conditions have likely persisted since the last glacial cycle, and in which occupation would always have been rare. This leads us to reconsider past land use patterns.

5.2 INTRODUCTION

Modelling the dynamics of human ecology is fundamental to understanding the record of human occupation in Australia and the most significant models have been developed for the Western Desert (Gould, 1977; Smith, 1988, 1989, 1993; Veth, 1989; 1993; Hiscock, & Wallis, 2005, Smith et al., 2017). Those models of past Aboriginal subsistence and settlement are often based on ethnographic observations and biogeographic-scale depictions of desert ecology. Such models have assisted in discussions of traditional forager subsistence and settlement practices, but the basis in ethnography limited measurement of change over time and regional level environmental characterisations have resulted in low resolution understandings of resource availability and land use. Australian researchers have increasingly employed spatial science methodologies to better portray ecological scenarios to interpret the archaeological past, although characterisation of ecological grain has still been coarse (Williams et al., 2013; Williams, Ulm, et al., 2015; Williams, Veth, et al., 2015; Bird et al., 2016; Bird et al., 2019). Technological advances in spatial science and environmental remote sensing offer a new level of sophistication to investigate past land use in a more spatially explicit way and at higher resolution. With more than a quarter-century of Earth observation imagery available in open

access formats, it is easier than ever to access and process massive datasets into sophisticated geospatial models of human ecology and land use. Our research takes advantage of these repositories, utilizing a number of free satellite image-derived products to investigate past land use in the Western Desert, including Geoscience Australia's (2015) Water Observations from Space, the United States Geological Survey's (2012) Landsat 5 TM Normalized Differential Vegetation Index (NDVI) datacube, and the Japan Aerospace Exploration Agency's (2019) Advanced Land Observing Satellite's digital surface model. Here, we use these remote sensing products to derive information on water accessibility, vegetation greenness, and terrain ruggedness. In combination, these variables are used to build a spatial ecological model that identifies suitable foraging habitats during times of maximum water abundance and above average vegetation health. Our suitability model has implications for how we think about and test for land use histories, and we contextualize the implications by summarising previous ideas of Aboriginal land use in the Western Desert.

5.3 BACKGROUND AND RATIONALE

The 'Western Desert' of Australia, as it is colloquially known, is one of the most arid and geographically remote regions on Earth. It includes areas of the Great Sandy Desert, Little Sandy Desert, Great Victoria Desert, Gibson Desert and the western portions of the Tanami Desert and the Central Ranges (Figure 5-1). The region spans nearly 1.1 million km², representing roughly 14% of the Australian land mass. Rainfall is seasonally unreliable, with a median annual rainfall around 250 mm (Bureau of Meteorology, 2019). Ambient temperatures in excess of 35°C are experienced more than 114 days annually and evapotranspiration is very high. The Western Desert is riverless, lacking any physiographic systems of coordinated drainage or permanent freshwater lakes (Madigan, 1936; Mabbutt, 1988; Morton, Smith et al., 2011). With the exception of a handful of springs, reliable water is almost entirely confined to montane uplands or rocky outcrops. In all other landforms, the availability of surface water is short-lived and entirely contingent on rain.

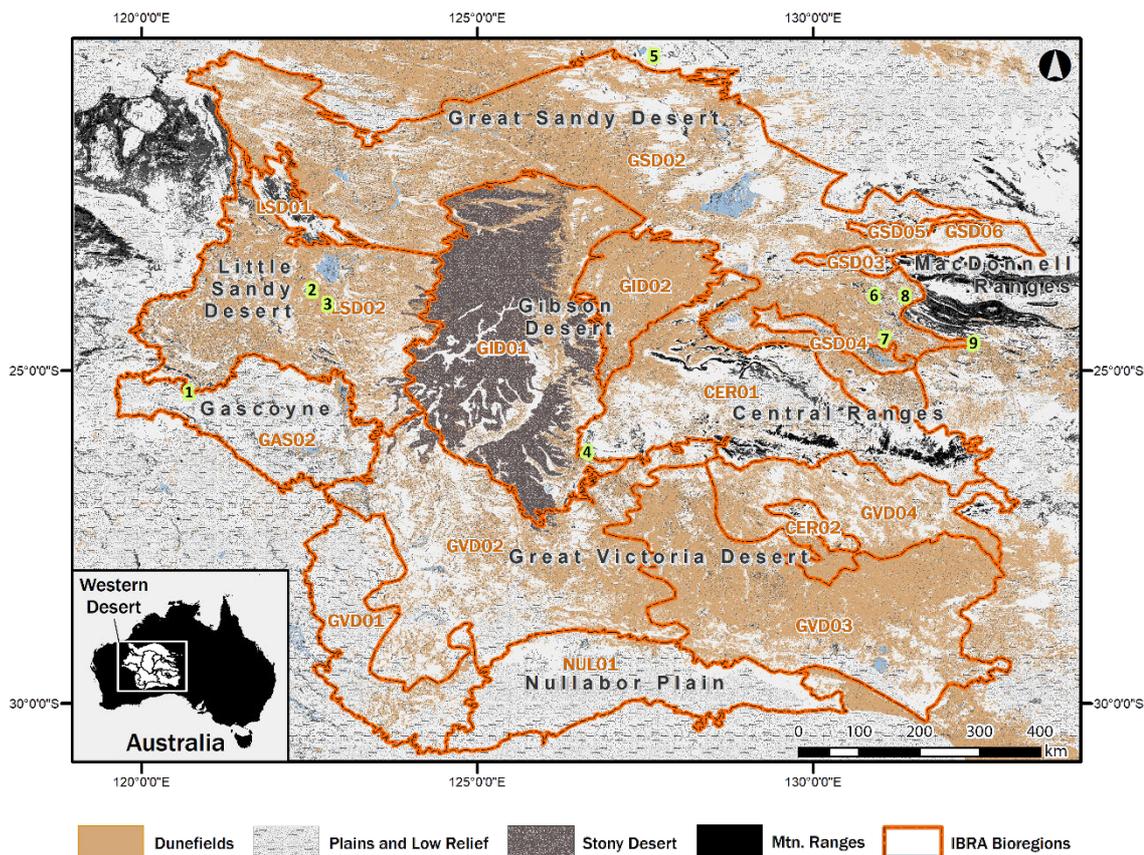


Figure 5-1 Location of the Western Desert in relation to continental Australia. The boundaries of the Interim Biogeographic Regionalisation for Australia (IBRA) are shown in relation to major land systems and desert regions (after Hesse, 2010). Excavated archaeological sites (green) are: (1) Karnatukul (Serpent's Glen), (2) Bushturkey-3, (3) Kaalpi, (4) Puntuntjarpa, (5) Parnkupirti, (6) Puritjarra, (7) Glen Thirsty, (8) Tjungkupu, and (9) Kulpi Mara.

These arid environmental conditions have always presented a challenge for human survival, so with understandable curiosity both scholars and the general public have been fascinated with the traditional foraging lifeways of desert Aboriginal groups. Did the ancestors of historic foragers occupy all desert areas? Was human occupation continuous over time? What land use strategies did resident groups employ and how did they enable people to live in a harsh environment? It was in pursuit of questions such as these that many anthropological and ethnoarchaeological studies were carried out during the past 50 years.

Historical and late Holocene desert societies have been characterised as small, nomadic, family groups of 10 to 30 individuals who foraged across large territories of land (Gould, 1977, p.21-22). This depiction allowed for groups to occasionally gather together in larger congregations, in excess of 150 individuals, but for short periods and only during times of increased water abundance (Gould, 1977, p.21). Most interpretations of Western Desert archaeology presume the total population

remained comparatively low throughout time, but some researchers have argued that population sizes increased substantially in the last 1500 years (Smith & Ross, 2008; Smith et al., 2008; Williams, Ulm, et al., 2015). Western Desert peoples of the twentieth century have been depicted as being highly mobile foragers who were opportunistic in both movement and resource targeting to give them sufficient flexibility to exploit the variable resources in this landscape (Gould, 1969a, 1969b, 1977). It has been argued that these economic strategies are so essential in the desert environment that they were always present in past behavioural systems. That proposition led Gould (1977) to propose the idea that persistence of the behavioural system reflected a culturally conservative nature of precontact desert societies, which could not afford to change its social, economic, and technological systems across space and time. It has been noted that serial changes in the archaeological record refute that model of desert conservatism (Hiscock and Veth 1998; Hiscock 2008), and that shifts in behavioural strategies might be expected as a way to respond to variability in the palaeoenvironment states (Hiscock, & Wallis, 2005).

Recent research indicates that the north and northwestern margins of the Western Desert were initially occupied by at least 45 ka (Veth et al., 2009; McDonald et al. 2018), and many researchers suggest there was widespread occupation of all desert areas prior to ~35 ka years ago (Smith, 1988; Smith & Sharp, 1993; Thorley, 1998; Hiscock & Wallis, 2005; Hiscock, 2008; Smith, 2013), during a wetter climatic phase where regional rainfall was more reliable and surface water was in greater abundance (Hesse et al., 2004; Cohen et al., 2011; De Deckker et al., 2011). These more favorable climatic conditions were interrupted by the onset of the last glacial maximum (LGM), a long palaeoclimatic interval from ~35–16 ka with increased aridity, cooler-than-present temperatures, unpredictable and episodic rainfall, reduced vegetation cover, and windy conditions that encouraged the development of extensive dunefields across the continental interior of Australia (Wasson, 1984; Wasson, 1986; Hesse et al., 2004; Williams et al., 2009; Hesse, 2016). Around 21 ± 2 ka, hyperarid conditions peaked (Hesse et al., 2004; Smith, 2009; Williams et al., 2009), and it is believed that lowland desert areas, such as sand plains, stony desert and sandridge deserts were largely abandoned for better resourced mountainous terrains that functioned as refugia for resident populations (Smith, 1988, 1989, 1993; Veth, 1989, 1993, 1995; Hiscock & Wallis, 2005; Williams et al., 2013). It has been argued that all lowland systems were reoccupied shortly after deglaciation (Smith, 1988, 1993), coincident with improved patterns of rainfall ca 14 ka (Wyrwoll

& Miller, 2001). Alternatively, it has been proposed that the post-LGM reoccupation of desert lowlands was limited to sandplains and stony desert land systems, which functioned as foraging ‘corridors’ between refugia (Veth, 1989, 1993). Connected to this interpretation is an argument that sandridge deserts were biogeographical ‘barriers’ to reoccupation until ca. 5000 years ago, when desert-adapted innovations in stone tool technologies and social demographics encouraged expansion into sandridge land systems (Veth, 1989, 1993). However, several have criticised this latter proposition, arguing that late Pleistocene peoples were already well-adapted to arid conditions (Smith, 1993; Hiscock & Wallis, 2005).

Palaeoecological data suggests the climate of the past 1500 years has been much like the present day (Smith, 2009). The rainfall patterns of the late Holocene are characterised by higher precipitation than the preceding mid-Holocene period, where monsoonal activity weakened or ceased during an arid climatic phase 5000 to 3000 years ago (Nott 2011, Fitzsimmons et al. 2013). Climate records of the past 1500 years also indicate that late Holocene precipitation has been more variable and less reliable than the terminal Pleistocene and early Holocene, when more humid conditions prevailed (Smith, 2009; Nott 2011; Fitzsimmons et al. 2013). Based on what is known of previous palaeoclimatic phases, modern environmental remote sensing data are most analogous to the late Holocene, but in certain contexts may be appropriate for deep-time comparisons.

Our understanding of Western Desert human ecology has been strongly influenced by regional ethnographic and biogeographic perspectives, which together have led researchers to accept a number of assumptions about Aboriginal land use practices in this arid environment (Gould, 1969a, 1969b, 1977, 1980; Peterson, 1976; Hiscock & Wallis, 2005). In brief, the suppositions underscoring nearly all previous ecological models include: (1) traditional forager subsistence and settlement was principally tethered to water availability and closely followed by accessibility to plant resources (Gould, 1969a, 1969b, 1977; Peterson, 1976), (2) past populations prioritized their foraging activities around ephemeral waters, and as these temporary ‘satellite’ resources depleted, foragers reorganised their land use around semi-permanent and permanent waters to reduce the risk of resource uncertainty during drier conditions (Gould, 1969a, 1969b, 1977), (3) permanent waters were generally restricted to montane desert ranges which likely functioned as ecological refugia at times in the past (Smith, 1988, 1989, 1993; Veth, 1989, 1993), and (4) variability amongst arid land systems and biogeographic areas presented

distinctive economic challenges for resident populations, and the manner in which people adapted to and behaved in particular desert terrains are likely to be expressed in the archaeological record (Smith, 1988, 1989, 1993; Veth, 1989, 1993; Thorley, 2001; Hiscock & Wallis, 2005; Law, 2009). This last point, which we argue throughout this article to be problematic, has led to a coarse-grained understanding of Aboriginal ecology and the arid zone archaeological record, where a range of expected human behaviours are inextricably linked to broad biogeographic regions, landforms, or environmental conditions (Veth 1989, 1993).

All previous ecological models recognize the importance of water for the successful arid settlement and subsistence. There is little argument that can be made against the resource's importance. Without access to water, Aboriginal groups would not have been able to effectively forage and survive in this arid landscape. Accordingly, some researchers emphasise the importance of the 'connectedness' of water resources across the arid zone, hypothesizing that water availability was the principal driver of human movement throughout desert regions (Bird et al., 2016). However, human behaviour is complex, and in all likelihood, additional environmental, geographical, technological, and demographic factors greatly influenced how land use and residential mobility was expressed (Hiscock, 2008).

For example, water abundance was not only important for human life, but it was equally important for local flora and fauna, upon which past Aboriginal groups also relied. Most models infer there is correlation between water and vegetation, which is a plausible proposition in this arid environment (Gould, 1969a, 1969b, 1977; Peterson, 1976). Vegetation health is affected by water availability, so it is understandable people would want to position themselves in way to maximise their plant foraging opportunities, not to mention hunt wild game attracted to the same resource.

It is also reasonable that differences in land systems and the general ruggedness of landscape would also affect land use and subsistence-settlement patterns. Therefore, the energy requirements of traversing rugged terrains must be considered when moving across substantial distances. Moreover, the availability of water and distribution of plant communities varies between land systems due to soils, geology, and related terrain characteristics. Thus, as researchers before us, we suggest the variability of desert terrains affected past foraging behaviours, either knowingly or unconsciously, and influenced where groups situated themselves amongst water and plant resources.

Our research considered these earlier suppositions which invariably influenced the structure and interpretation of our foraging suitability model. When modelled under the best known environmental conditions, we hypothesized that our ecological model would spatially depict a wide range of suitable foraging habitats across the Western Desert and provide some indication of where desert dwellers could best position themselves amongst natural resources. We reasoned that this information would allow for us to critically evaluate the likely extent and permanency of Aboriginal occupation in the vast arid region and determine if land use was tied to particular land systems or bioregions, as suggested by others. Through the lens of this work, we suggest that our foraging suitability model holds implications for our understanding of precontact land use practices and the deep-time archaeological record itself.

5.4 RESULTS AND DISCUSSION

Our foraging habitat suitability model is the integrated product of satellite-derived environmental data, geomorphometric terrain analysis and historic anthropological information (Figure 5-2). The model's environmental foundation is based on more than two decades of continuous bi-weekly satellite observations, allowing for the systematic detection and measurement of water recurrence and vegetation condition for every 30 x 30m pixel area captured in the images. This period of observation is long enough to observe multiple fluctuations in this highly variable environment and to not be restricted to a single short-term climatic state, such as a bushfire or drought. Therefore the time frame provides a reliable observation and measurement of maximum vegetation greenness, regardless of temporary drops in NDVI. Similarly, maximum extent and occurrence of surface water is systematically measured through long-term satellite observations, avoiding measurements only of phases of drought or irregular rainfall. For this reason our model focuses on maximal values to represent the best conditions that would have been available for past foraging activities.

The model also uses ~30m satellite digital elevation data to quantify terrain ruggedness across the study area (Riley et al., 1999). Terrain ruggedness is a geomorphometric measure of land surface ruggedness, where elevation variability is used to infer ease of traversal when walking between locations in the landscape. Terrain ruggedness is suggestive of potential energy expenditure, assuming that increasingly rugged terrains necessitate higher levels of physical activity and caloric

intake. Here, we integrated measures of ruggedness with environmental satellite data, providing an indication of which patches of vegetation and water are most easily accessed in regards to minimum changes in elevation.

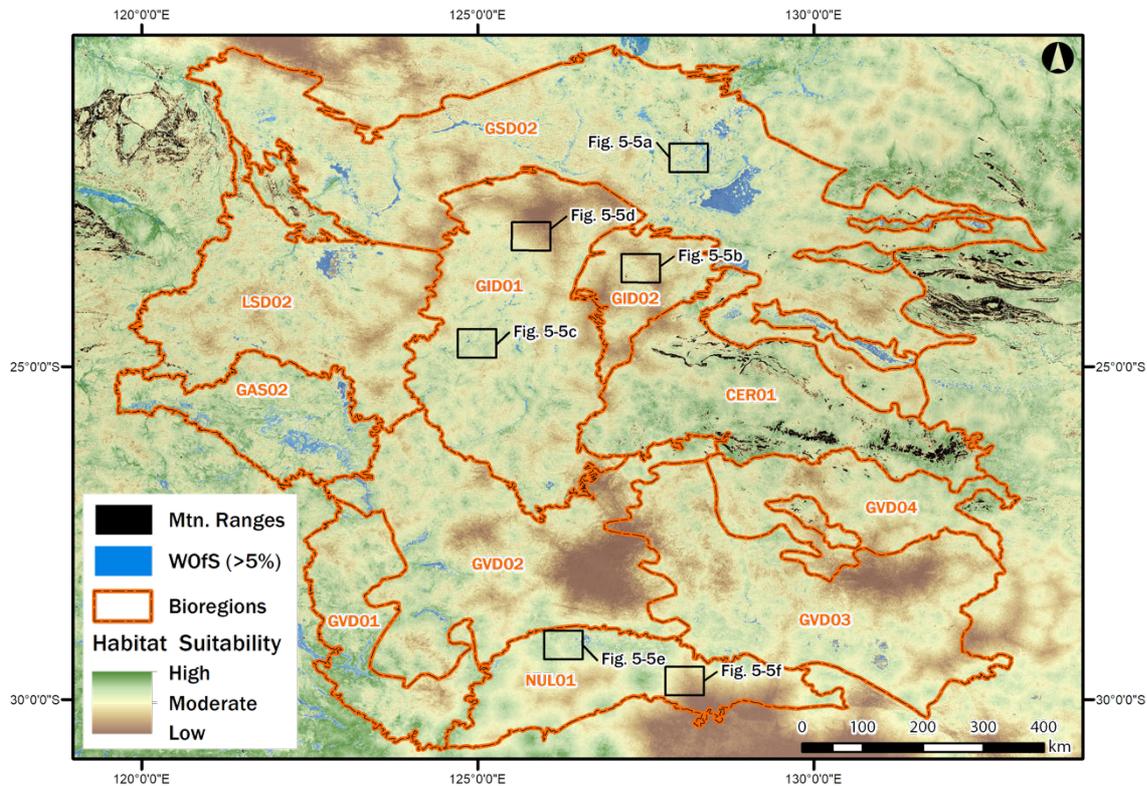


Figure 5-2 A satellite derived model of foraging habitat suitability for the Australian Western Desert.

Walking time to observed surface water is the final spatial parameter incorporated with the model. It is calculated using Tobler’s (1993) hiking algorithm and information on daily foraging practices. Historic anthropological data indicates Western Desert foraging activities operated for 4 to 6 hours each day (Gould, 1977; Binford, 2001), with foragers moving up to a day from ephemeral water sources in their food quest (Gould, 1977). In accordance with these ethnographic statements we spatially delineated land areas where regular foraging activities may have occurred within 8 hours walk of a temporary water resource, giving greater weight to such localities. Since resources are said to be permanent in uplands, we assume mountainous refugia were always suitable foraging habitats, so these refugia areas have been masked and removed from consideration in the study (see montane areas in Figure 5-2).

Appropriate elements from all of the aforementioned satellite information sources were combined to produce the foraging habitat suitability model

(Figure 5-2). The ~30m spatial resolution of the data facilitates the construction of a spatially-explicit, geographically broad, yet fine-grained ecological model to critically appraise foraging habitat suitability at a variety of scales, offering new perspectives on regional human behavioural ecology. The model provides a continuous ranking of the relative foraging value for each landscape patch (or 30m pixel in this instance). Interpretation of patch values is based on the proposition that foragers know the conditions in all parts of the landscape they visit, and they organized their daily foraging movements in accordance with the parameters outlined above.

As Figure 5-2 indicates, foraging habit suitability is highly variable. To simplify and gain a coarser-grained understanding of the distribution of this variability, we grouped the patch values into low, moderate, and high foraging habitat suitability classes and calculated the non-masked land area occupied by each class (Table 5-S1). Results show that during times of maximum water abundance and vegetation greenness, 36.6% of the Western Desert has high-ranked habitat suitability. Moderately suitable areas constitute 48.9% and low-ranked patches encompass 13.1% of the study area.

Breaking these finding down further, Figure 5-3 illustrates the percentage of the habitat suitability classes that occupy the eleven largest bioregions of the Western Desert (Table 5-S1). Higher-ranked locations are well positioned in relation to suitable resources and easily traversed terrains. Lower-ranked locations are considered poorly suited habitats due to their considerable distance from water and plant resources, and they are in comparatively rugged terrains. Areas deemed to have moderate foraging suitability have mixed accessibility to resources and variable terrain ruggedness.

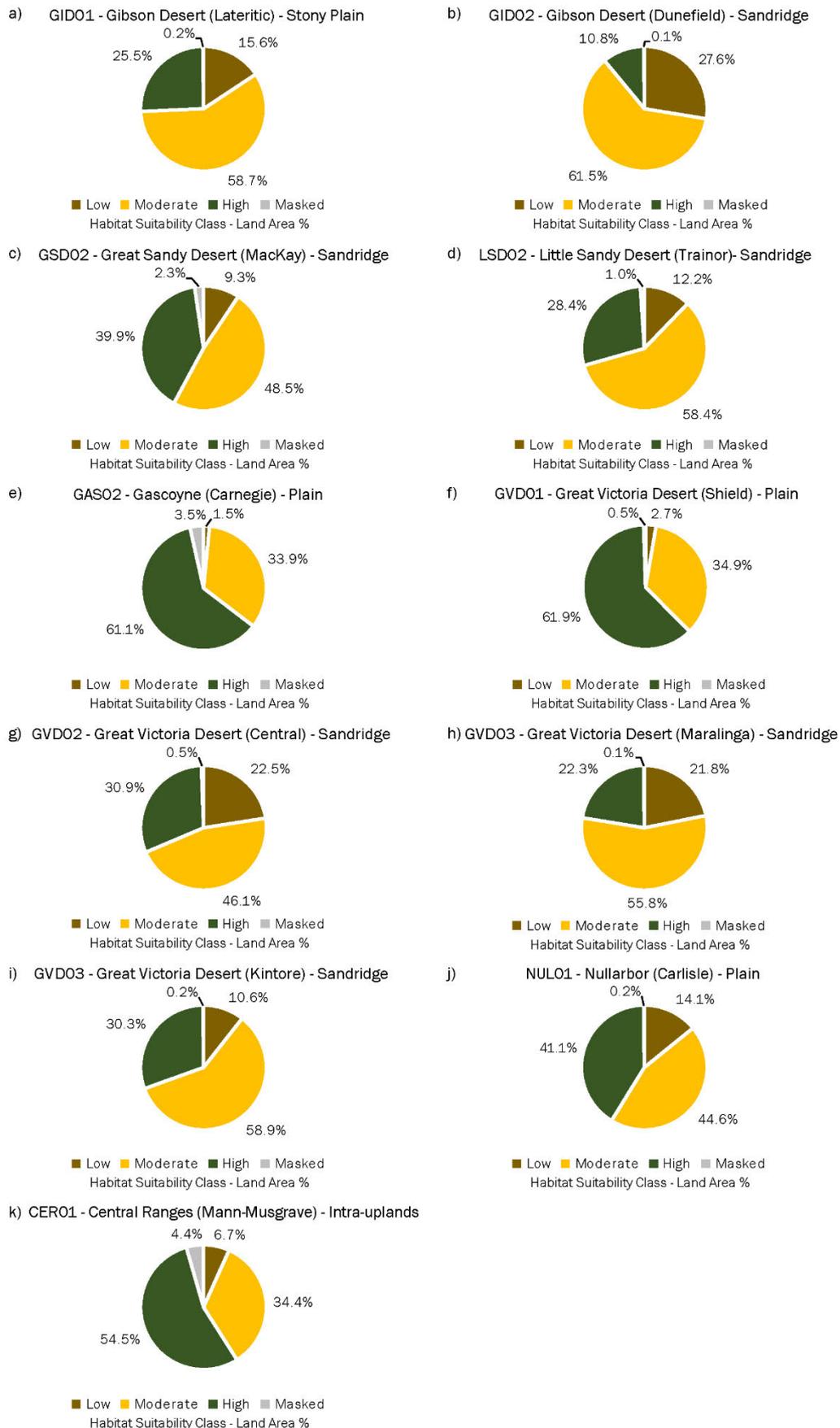


Figure 5-3 Percent of land area occupied by low, moderate, and high-ranked habitat suitability areas for the eleven largest IBRA bioregions, together with dominant landform type (see Table 5-S1).

At a bioregional level, intra-upland zones (CER01) and desert plains (see GAS02, GVD01, and NULO1) offer a greater percentage of high-ranked foraging habitats per land area (Figure 5-3). Bioregions dominated by dunefields have considerably less high ranked land areas compared to uplands, plains, and areas of low relief, although it is important to note that there is also considerable patchiness amongst suitable foraging areas in sandridge desert regions (see Figure 5-2). For instance, the centrally located Gibson Desert dunefield area (GID02) has very little area of high-ranked habitat (10.8%), which is far less than other sandridge desert bioregions (see GSD02, LSD02, GVD02, GVD03, and GVD04) where high suitability ranges between 39.9% and 22.3% (Figure 5-3). Similarly, the centrally positioned Gibson Desert stony desert bioregion (GID01), which is dominated by lateritic surface gravels, records only 25.5% high-ranked habitat areas. Thus, from a coarse-grained ecological perspective, it seems that the central core regions of the Western Desert are generally the more hostile and offer less highly suited foraging opportunities compared to more peripheral bioregions.

5.4.1 Widespread Foraging Amongst an Uneven Distribution of Suitable Habitats

When viewed at a fine-grained scale, our model clearly shows that there is an uneven gradient of suitable foraging habitats across the Western Desert (see Figure 5-2). Away from montane uplands, water permanence is always temporary, and land systems with low topography, such as plains, stony plains, and sandridge desert, have highly varied foraging suitability, even when characterized in the best environmental conditions.

The implications of this variation are important to understanding human ecology of the ethnohistoric period and the late Holocene archaeological record of the past 2000 years, when climatic conditions and landscapes were much like the present day (Hesse, Magee, & van der Kaars, 2004; Smith, 2009; Nott, 2011). Many scholars have noted that the desert peoples of this time period were familiar with the distribution of regional natural resources (Smith, 1993, 1996; Hiscock & Wallis, 2005). It has been argued that resource knowledge was articulated with socioeconomic strategies, and that groups routinely utilized all areas of the Western Desert during times of good rainfall and resource abundance. However, our suitability model reveals that there are large, expansive areas of the desert landscape that would have presented substantial challenges for survival, even in the best of historical environmental circumstances (see brown areas Figure 5-2). Our model

further suggests that low-ranked locations of foraging suitability were always below average productivity and were always comparatively unsuited as foraging habitats, as discussed below.

In our modeled scenario, we used satellite observations of maximum vegetation greenness to indicate of land productivity for our three suitable foraging habitat classes. Figure 5-4 illustrates the mean NDVI derived from our time-series satellite dataset of maximal vegetation greenness (Table 5-S2) for low, moderate, and high habitat suitability classes amongst the eleven most prominent Western Desert bioregions. For comparative purposes, the means (\bar{X}) of NDVI for each bioregion and entire Western Desert are also denoted in Figure 5-4.

Given the below average NDVI of all low-ranked desert lowlands, we hypothesize that broad clusters of extremely unsuitable localities would be unlikely to provide adequate returns (Figure 5-4), even when foragers were pursuing low-variance or lower quality resources (Bliege Bird & Bird, 2008). Based on the distribution of low-ranked suitability areas (see Figure 5-2), we infer the existence of several massive land tracts that are poorly-suited as foraging environments and, if ethnographic patterns of land use were in place, we predict many of these large areas would have been rarely utilized or perhaps some were purposefully avoided due to known deficiencies in the resource energy base (Coddling et al., 2016). One implication of these persistently unsuitable areas is recognition that the entire desert region was not equally economically viable for foraging, and that substantial tracts of land were not economically attractive for foragers. This proposition is readily testable because it predicts that archaeological sites with poorly sorted, low densities of artefacts will be found in these places (Coddling et al., 2016). At a coarse-grained scale, the distribution and patchiness of massive-sized sub-optimal patches may be an important factor shaping the patterns of movement through the landscape, with foragers potentially preferring movement along high suitability corridors. However at a finer grained scale, small areas of low suitability, which are often a local geographic feature (e.g., sand dune, bare rock outcrop, or erosional area), may not necessarily be treated as an obstacle.

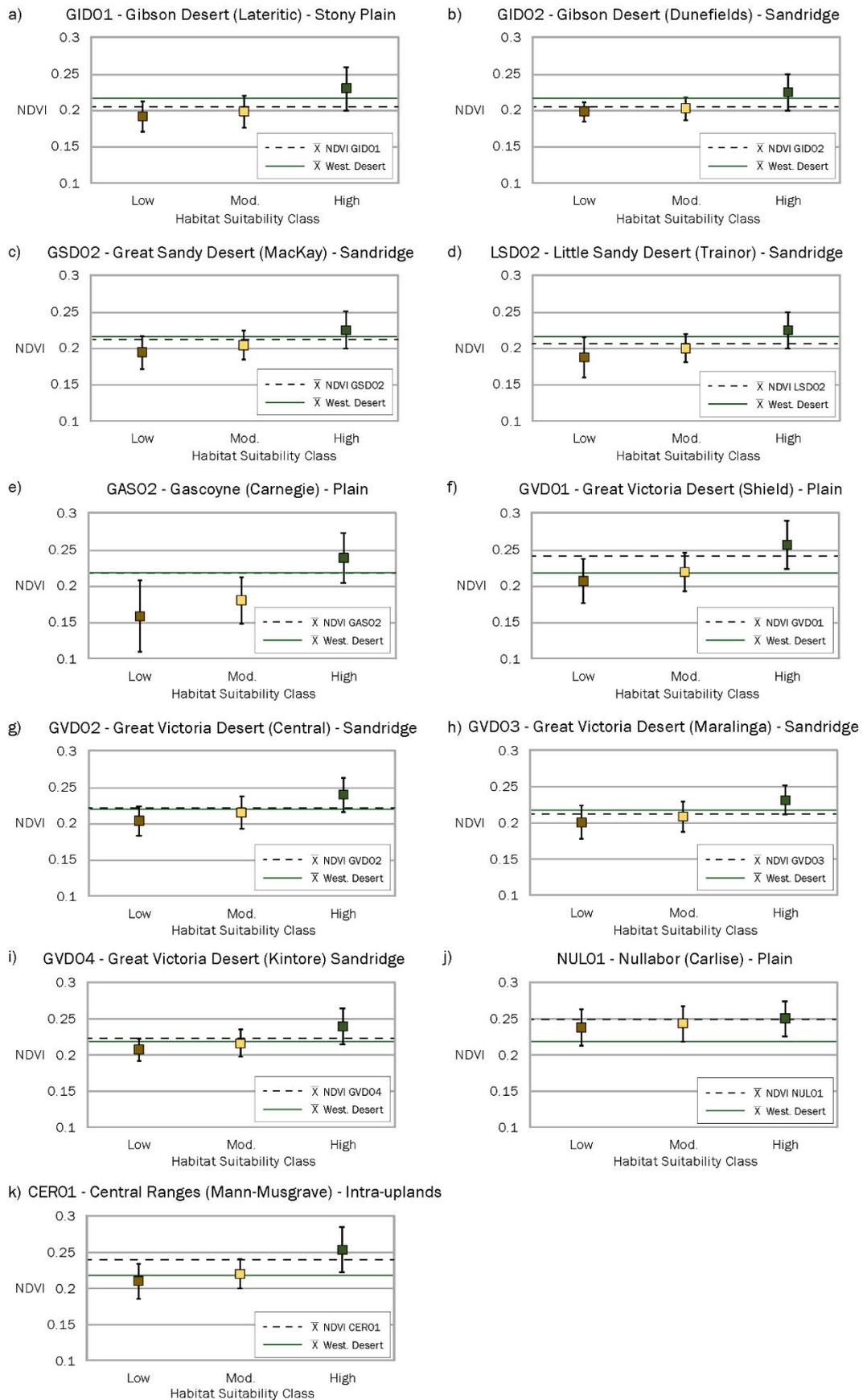


Figure 5-4 Boxplot of mean NDVI values and one standard deviation of NDVI for low, moderate, and high-ranked suitability within the eleven largest IBRA bioregions in the Western Desert. Mean (\bar{X}) NDVI for individual bioregions and the spatial bounds of the Western Desert study area denoted as dashed line and a green line, respectively (see Table 5-S2).

At present, the archaeological pattern of low-ranked foraging habitats is not something that is well-understood from the Western Desert, although periodic and short term use of impoverished, low productivity patches has been predicted (Coddington et al. 2016). Elsewhere, in the eastern Australian arid zone, periodic use of climatically harsh desert localities is known from archaeological sequences. For instance, in the western Strzelecki Desert broad portions of dunefield landscapes were periodically abandoned for centuries or even millennia (Hughes et al., 2017), while in semi-arid portions of southeastern Australia sequences of occupation were separate by decades or centuries of local/regional abandonment (Fanning & Holdaway, 2002; Holdaway et al., 2005; Fanning et al., 2013). Fluctuations in local foraging suitability may well be a factor producing discontinuous land use across the Australian arid lands, and we suggest that in the Western Desert there were patches with variable foraging potential. The key test of this prediction would be to investigate whether archaeological sites with discontinuous evidence of visitation exhibit highly varied fluctuations in habitat suitability over time. Such a study could be achieved through a time-series analysis of vegetation greenness from the past few decades, where the variability of NDVI for archaeological sites located in low-ranked habitats is compared to neighboring high-ranked patches.

5.4.2 How Earth Observation Imagery Changes Our Spatial Perspectives of Land Use

Australian archaeological research has relied heavily on biogeographic principles to distinguish the ‘barriers and boundaries’ of Aboriginal subsistence and settlement in the arid zone (Veth, 1989, 1993; Veth, O’Connor, & Wallis, 2000). While equating particular land use practices with specific bioregional areas was initially useful for generalized conceptualisations of traditional foraging behaviours, it is now problematic. The approach has been aptly criticized by Smith (1993) for its use of vaguely defined biogeographic categories, causing confusion when describing landform features, land system, and bioregional characteristics. Additionally, researchers have warned that biogeographic generalisations can be overly simplistic, failing to see subtle environmental variations within land systems themselves (Rhoades, 1978; Hardesty, 1980; King & Graham, 1981; Marwick et al., 2017).

Previous biogeographic representations of Aboriginal ecology have been applied in a uniform manner to broad swathes of the Western Desert (Veth 1989, 1993). The problem with such coarse-grained approaches is that they lack a more

nuanced understanding of the range of potential foraging behaviours. Our model overcomes this issue of scale by allowing for a much finer-grained and more spatially explicit examination of the bioregional landforms to infer past land use. For example, as we focus at higher resolution on various areas of the Western Desert, our model clearly shows that foraging suitability is highly varied across all desert lowlands (Figures 5-2 and 5-5). In sandridge desert areas, which Veth (1989, 1993) proposes to have been a barrier at times in the past, the model shows there are many well-watered and amply vegetated localities where good foraging is possible when rainfall is high and surface water is abundant (Figure 5-5a). In this context, interdunal swales are hardly barriers to occupation because they are plush with water, plant, and wildlife resources, and the energy expenditure required to walk along interdunal swales is low in comparison to the requirements needed to repeatedly scramble across a sea loose sands and undulating dunes. Thus, it seems entirely plausible that that resident groups could navigate and forage in many dunefield areas by following a well-resourced network of swales during times of good environmental conditions. The fine-grained nature of this observation opens up the possibility that many sandridge desert are were not necessarily broad barriers to occupation and that precontact land use behaviours varied in different dunefield contexts (cf. Veth 1989, 1993).

We also highlight that the resource-rich swale pattern is not widespread across all dune systems, and it is plausible that some of these areas were periodic barriers to occupation, as previously suggested in more generalized ecological models (Veth 1989, 1993). There are substantial areas of sandridge desert, especially within central areas of the Western Desert (e.g., GID02), where survival would have always been extremely difficult, even during times of abundance (Figure 5-5b). This variability is also expressed in stony desert contexts, where southern areas of the lateritic Gibson Desert (GID01) offer better habitat suitability (Figure 5-5c) than the northern areas (Figure 5-5d). On a fine scale, plain land systems also exhibit a wide range of habitat suitability, where high-ranked habitat suitability appears fairly widespread in some areas of the Nullabor Plain (Figure 5-5e), yet other areas of the plain were poorly suited for foraging (Figure 5-5f).

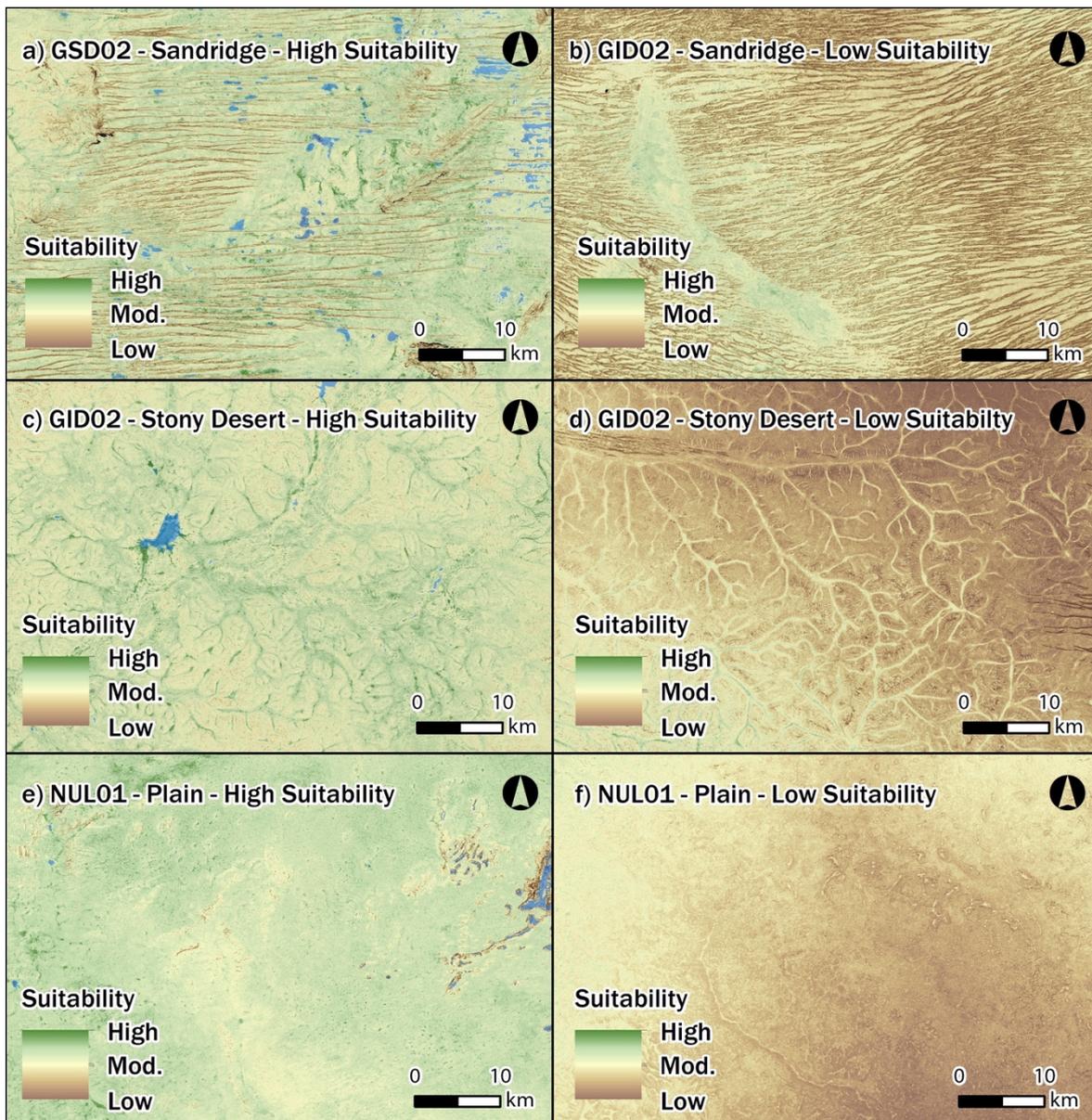


Figure 5-5 Enlarged perspectives of higher-ranked and lower-ranked suitable foraging areas in the various Western Desert landform contexts. This figure illustrates the fine-grained scale of our habitat suitability model, which has implications for better understanding localised land use behaviours (see Figure 5-2). Juxtaposed areas are: (a) High-ranked sandridge habitats vs. (b) low-ranked sandridge land system. (c) High-ranked stony desert habitat vs. (d) low-ranked stony desert areas. (e) High-ranked sand plain land systems vs. (f) low-ranked plain habitats.

In previous ecological models, stony desert and plain land systems are considered more favourable than sandridge desert (Veth, 1989, 1993); however, as shown above, the modelled data clearly illustrates that there are substantial areas of plains and stony desert landscapes that vary considerably between high and low-ranked habitat suitability (see Figures 5-2 and 5-5). We suggest the fine-grained scale of our model shows how previous generalised characterisations of foraging ‘corridors’ and ‘barriers’ oversimplify the link between human behaviour and biogeography. Extremely unsuitable foraging and very well-suited foraging areas can potentially occur in any area of the Western Desert, regardless of the

biogeography or other physical characteristics. Fine-grained ecological models allow for a more spatially-explicit understanding of the past land use behaviours that led to the formation the desert archaeological record.

5.4.3 Using Satellite Data as a Deep-time Analog for Archaeological Investigations

There is no doubt that the Western Desert environment has changed and evolved throughout time, by both natural and human-induced processes (Hesse et al., 2004; Bliege Bird et al., 2008; Williams et al., 2009; Crabtree, Bird, & Bird, 2019). The region has endured considerable environmental fluctuations, including changes in vegetation cover and dune aggradation across much of the area. These environmental changes clearly place limitations on how modern satellite data can be used to interpret deep-time patterns of occupation and land use. However, we do believe it is reasonable to ask, “How plausible are earlier ecological models in relation to our understanding of the environmental record of the past few decades?” And if some land use scenarios seem unlikely in the recent past, then what are the implications when palaeoenvironmental conditions were much harsher than present?

Here is where our foraging suitability model offers an intriguing deep-time archaeological possibility to consider, one that suggests that some poorly suited foraging areas have not been effectively inhabited since the LGM. Our model shows there are several large areas of the Western Desert where, in combination, surface terrains are physically challenging, the nearest proximity to surface water is greater than two days walk, and vegetation health is substandard—and this in the best documented environmental conditions! During the LGM, the reliability and resource yields in such areas would have been more diminished than present, making conditions for survival even more difficult than today. Based on the findings of our habitat suitability model and our understanding of ancient palaeoenvironmental patterns, we suggest it is reasonable to hypothesize that some areas of the Western Desert may not have been occupied since prior to the onset of the last glacial cycle, ~35-16 ka.

Such a hypothesis is easily tested with comprehensive archaeological fieldwork, but regional investigations needed to validate such a suggestion are scarce. Around a dozen archaeological sites are reported to have been investigated in the Western Desert (Smith, Williams, and Ross 2017), with none located in the harsher core areas identified in this study (Gould, 1977, 1978; Smith, 1987, 1988,

2004; Veth, 1993, 1995; O'Connor, Veth, & Campbell, 1998; Veth, Smith, & Haley, 2001; Smith, & Ross, 2008; Veth, McDonald, & White, 2008; Veth et al., 2009; Smith, Williams, & Ross, 2017; McDonald et al., 2018). For this reason, we argue that future archaeological fieldwork in the low-ranked landscapes identified in this study is not only warranted, it is necessary and highly important to our understanding of the deep-time and recent occupation of this vast and remote area of Australia.

5.5 SUPPLEMENTARY INFORMATION

5.5.1 Materials and Methods

Software and Data Sources

ArcMap 10.5.1 with the Spatial Analyst Extension was the principal software package used for analysis and spatial modeling (ESRI, 2016), with additional software used for some pre-processing tasks. The Landsat NDVI time series was accessed via Google Earth Engine (GEE), a cloud-based geospatial platform (Gorelick et al., 2017). QGIS 2.4, also an open-platform GIS package, was used for terrain ruggedness processing (QGIS Development Team, 2014).

Each of the Earth observation datasets described below offer continental-wide spatial coverage and are available as georeferenced ~30m spatial resolution packages. For ease of processing, our area of interest was clipped and mosaicked as appropriate, and raster cell grids were aligned using the snap raster function in ArcMap 10.5.

Water Observations from Space (WOfS) is a Geoscience Australia time-series dataset developed from imagery acquired by NASA's Landsat 5 and Landsat 7 satellites from 1987 to 2014 (Geoscience Australia, 2015). The summary dataset product, used here, was produced from more than 184,500 scenes collected over this 27 year period (Mueller et al., 2016). The summary product is a single band raster depicting the recurrence of detectable surface water in an area of land. The water observations are recorded as a percentage for each grid cell, which Geoscience Australia calculated by using the ratio of detected surface water observations to the number of clear observations for all acceptable Landsat scenes.

The Landsat 5 TM 8-Day NDVI composite image collection is a time-series datacube or pre-processed NDVI scenes collected between 1984 and 2012 (United States Geological Survey, 2012). The Landsat 5 TM 8-Day NDVI collection was

produced by the United States Geological Survey using top-of-atmosphere reflectance to calculate NDVI at 30 m spatial resolution globally (Chander et al., 2009). The collection is stored in Google Cloud, where it can be freely accessed and processed via GEE (Gorelick et al., 2017). NDVI is a widely used remote sensing index that evaluates vegetation greenness. It is a measured inference of plant cover, biomass and health, based on how light is reflected in the near-infrared (NIR) and red (Red) spectrum of the Landsat 5 imagery. NDVI was calculated using the ratio: $(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$. NDVI values range -1.0 to 1.0, where higher values indicate healthy vegetation and values near or slightly above 0.0 suggest bare earth.

The Advanced Land Observing Satellite (ALOS) World 3D 30m grid digital surface model (DSM) product is available free of charge from Japan Aerospace Exploration Agency (Japan Aerospace Exploration Agency, 2019). The product is a 30m resolution continuous topographic model of the Earth with ± 5 m vertical height accuracy (Takaku et al., 2014; Tadono et al., 2016).

Derived Variable 1 (var1) – Water Accessibility

WofS time-series summary raster data was visualized in ArcMap and filtered to display all localities where surface water has been detected in greater than 5% of satellite observations. These localities represent the maximum abundance of surface water. For classificatory purposes, the water bodies were converted to a binary raster showing detected water locations ($n = 1$) and cells with no detectable water ($n = 0$). Walking time to detected water localities was calculated using the ArcMap's path distance tool, using the ALOS DSM and Tobler's hiking function as vertical factor parameters (Tobler, 1993). The end-product is a single-band continuous raster with cell values representing the walking time (hours) to the nearest detected source of water. Raster values ranged from 0.0 to 36.5 hours walking distance to nearest water. ArcMap's fuzzy linear membership function was used to reclassify and transform walking data to a 0 to 1 scale based on criteria supported by ethnographic foraging observations (Gould, 1977; Binford, 2001). Localities between 0 to 16 hours walking time were reclassified along a linear scale of partial membership, where land areas immediately adjacent to waterhole were assigned a full membership value of 1, areas 8 hours distant were assigned a partial membership value of 0.5, and areas greater than 16 hours walking distance were classified with a membership value of 0.0, indicating they are undesirable due their distant proximity to water.

Derived Variable 2 (var2) – Maximum Vegetation Greenness

Landsat 5 TM 8-Day NDVI composite image collection (1 January 1984 – 8 May 2012) was analyzed using the Google Earth Engine code editor (Gorelick et al., 2017). The image collection was processed with the 'reducer.percentile' function code to produce a single band raster showing 95th percentile NDVI values. This composite NDVI image represents the maximum vegetation greenness values observed over more than two decades. The 95th percentile NDVI image was exported as a georeferenced .TIF file and the ArcMap 10.5 fuzzy linear function used to reclassify and transformed the NDVI values to a 0 to 1 scale. NDVI values greater than or equal to 0.3 were assigned a membership value 1, suggesting healthy vegetation (note: the mean NDVI of healthy grass in arid Australia is 0.29 (Newnham et al., 2011)). Assignment of fuzzy membership values was decreased along a linear scale between NDVI values of 0.3 and 0.0, where, for example, an NDVI value of 0.15 was assigned a partial membership value of 0.5 and NDVI values equal to or below 0.0 were assigned a membership value 0, indicating bare earth.

Derived Variable 3 (var3) – Terrain Ruggedness

The terrain ruggedness index (TRI) is a measure of topographic variability, calculated as the mean difference between the elevation of a central pixel and its surrounding cell elevations. The ALOS DSM was used to calculate the TRI raster in accordance with previously published conventions (Riley, De Gloria, & Elliot, 1999). The TRI .TIF raster was created in QGIS using the terrain analysis tool package, and TRI cell values were analysed for landform patterning. In the context of the Western Desert, TRI values less than 3.5 equate to relatively level land surfaces, values 3.5 to 17 demarcate sand dunes, and values greater than 17 delineate escarpments and upland areas. A fuzzy linear function was applied to reclassify and transform the TRI data to a 0 to 1 scale. A TRI value of 0 is considered to have a membership value of 1, indicating easily traversed, flat terrain. Fuzzy membership values scaled downward between TRI values 1 and 17, where, for instance, a TRI value of 8.5 was assigned partial membership of 0.5. All TRI values greater than or equal to 17 were assigned a membership value of 0, indicating rough upland terrains, which correspond well with refugia areas.

Modelling Foraging Suitability and Classifying Suitability Areas

The foraging suitability model, S , was built using the ArcMap raster calculator and the equation:

$$S = \frac{(var1 + var2 + var3)}{N}$$

Where $var1$, $var2$, and $var3$ correspond to the derived variables described above and N is the total number of input variables, which in this instance is 3. The raster calculator produced our foraging suitability model as a single band continuous .TIF image, with values scaled between 0 and 1. The result is a negative skewed distribution of values, where the median is 0.803. The Jenks natural breaks method was used to cluster data and classify the data values. Data values greater than 0.829 are interpreted as high-ranked habitat suitability. Values between 0.710 and 0.829 are ranked have moderately-ranked habitat suitability. Values lower than 0.710 represent areas with low-ranked habitat suitability.

Zonal Statistics

ArcMap's 'zonal statistics as table' function was used to extract land area statistics and maximum greenness values from the 95th percentile NDVI values ($var2$). The function uses a defined raster zone (e.g., IBRA region or habitat suitability class) to extract and provide summary calculations for pixel values within a zone, which is defined as an input area where a group of cells have the same value. In this instance, IBRA regions (17 classes) and habitat suitability classes (low, moderate, and high-ranked) were used as zones to extract NDVI values and calculate the number of pixels, spatial area (km²), and mean, minimum, maximum, standard deviation of cell values for each respective zone. The results of these extracted values are presented in Tables S1 and S2. Unless indicated otherwise, maximum surface water observations ($var1$ values > 5) and montane uplands ($var3$ values > 17) were masked from analysis.

5.5.2 Supplementary Tables

Table 5-S1 Land area statistics for Western Desert IBRA bioregions and habitat suitability classes.

IBRA Code	Name	Pixel Count	Total Area km ²	Habitat Suitability Class							
				Low-Ranked		Moderate-Ranked		High-Ranked		Masked Area	
				km ²	%	km ²	%	km ²	%	km ²	%
CER01	Central Ranges (Mann-Musgrave) Intra-uplands	108491446	929978.54	62010.01	6.7%	319564.41	34.4%	507216.85	54.5%	41183.46	4.4%
CER02	Central Ranges (Watarru) Intra-uplands	4994548	42812.80	5851.41	13.7%	27695.32	64.7%	8601.79	20.1%	663.95	1.6%
GAS02	Gascoyne (Carnegie) Plain	55032835	471736.32	7232.95	1.5%	159957.65	33.9%	288097.43	61.1%	16446.62	3.5%
GID01	Gibson Desert (Lateritic) Stony Plain	148492069	1272860.15	199136.69	15.6%	746580.67	58.7%	324443.08	25.5%	2690.25	0.2%
GID02	Gibson Desert (Dunefield) Sandridge	34144136	292680.34	80700.25	27.6%	179959.70	61.5%	31755.19	10.8%	262.59	0.1%
GSD02	Great Sandy Desert (Mackay) Sandridge	301656747	2585773.46	241185.91	9.3%	1254072.34	48.5%	1031242.09	39.9%	59258.17	2.3%
GSD03	Great Sandy Desert (Ehernberg) Intra-uplands	4445630	38107.53	670.79	1.8%	9681.12	25.4%	27060.85	71.0%	694.66	1.8%
GSD04	Great Sandy Desert (Amadeus) Salt Lake	8542556	73225.99	2950.83	4.0%	25672.92	35.1%	38972.90	53.2%	5629.06	7.7%
GSD05	Great Sandy Desert (Lake Bennett) Salt Lake	3440296	29489.90	440.85	1.5%	1919.46	6.5%	25788.94	87.5%	1340.61	4.5%
GSD06	Great Sandy Desert (Lake Lewis) Salt Lake	989227	8479.56	268.67	3.2%	1995.92	23.5%	5131.71	60.5%	1083.24	12.8%
GVD01	Great Victoria Desert (Shield) Plain	55283579	473885.68	12769.19	2.7%	165519.02	34.9%	293210.26	61.9%	2385.42	0.5%
GVD02	Great Victoria Desert (Central) Sandridge	147028966	1260318.56	283778.73	22.5%	580458.33	46.1%	389169.36	30.9%	6903.50	0.5%
GVD03	Great Victoria Desert (Maralinga) Sandridge	135215812	1159057.31	252911.00	21.8%	646250.71	55.8%	258174.83	22.3%	1711.78	0.1%
GVD04	Great Victoria Desert (Kintore) Sandridge	58646558	502712.82	53083.64	10.6%	296209.12	58.9%	152488.36	30.3%	928.20	0.2%
LSD01	Little Sandy Desert (Rudall) Intra-uplands	11557071	99066.13	8599.47	8.7%	31637.56	31.9%	55344.26	55.9%	3484.45	3.5%
LSD02	Little Sandy Desert (Trainor) Sandridge	117770723	1009519.64	122677.38	12.2%	589679.98	58.4%	286865.64	28.4%	10289.51	1.0%
NUL01	Nullarbor (Carlisle) Plain	67764672	580872.44	81937.50	14.1%	259232.41	44.6%	238795.75	41.1%	903.38	0.2%
Western Desert	All IBRA Regions Combined	1263496871	10830577.17	1416205.27	13.1%	5296086.62	48.9%	3962359.30	36.6%	155858.86	1.4%

Table 5-S2 NDVI statistics for Western Desert IBRA bioregions and habitat suitability classes.

IBRA Code	Suitability Class	No. of Pixels	Area (km ²)	Min.	Max.	Range	Mean	St.Dev.
GIDo1	Low	23231318	19913.67	0.041	0.450	0.409	0.192	0.021
	Moderate	87096221	74658.07	0.043	0.516	0.473	0.198	0.023
	High	37849582	32444.31	0.147	0.568	0.422	0.230	0.030
	All GIDo1	148177121	127016.04	0.041	0.568	0.527	0.205	0.029
GIDo2	Low	9414504	8070.02	0.077	0.396	0.319	0.198	0.013
	Moderate	20994128	17995.97	0.079	0.464	0.385	0.202	0.016
	High	3704566	3175.52	0.147	0.473	0.325	0.225	0.025
	All GIDo2	34113198	29241.51	0.077	0.473	0.396	0.203	0.018
GSDo2	Low	28136787	24118.59	0.023	0.588	0.565	0.194	0.023
	Moderate	146300280	125407.23	0.039	0.673	0.634	0.203	0.020
	High	120304868	103124.21	0.146	0.763	0.617	0.224	0.025
	All GSDo2	294741935	252650.03	0.023	0.763	0.740	0.211	0.026
LSDo2	Low	14311563	12267.74	0.029	0.602	0.573	0.187	0.028
	Moderate	68792161	58968.00	0.039	0.583	0.544	0.199	0.019
	High	33465792	28686.56	0.147	0.589	0.442	0.224	0.025
	All LSDo2	116569516	99922.30	0.029	0.602	0.573	0.205	0.026
GASo2	Low	843797	723.29	0.040	0.607	0.568	0.158	0.049
	Moderate	18660685	15995.76	0.052	0.607	0.556	0.180	0.032
	High	33609493	28809.74	0.147	0.595	0.449	0.238	0.035
	All GASo2	53113975	45528.80	0.040	0.607	0.568	0.216	0.045
GVD01	Low	1489656	1276.92	0.057	0.404	0.347	0.206	0.030
	Moderate	19309475	16551.90	0.059	0.527	0.468	0.219	0.026
	High	34205956	29321.03	0.147	0.559	0.412	0.256	0.034
	All GVD01	55005087	47149.85	0.057	0.559	0.502	0.241	0.036
GVD02	Low	33105672	28377.87	0.051	0.454	0.403	0.204	0.020
	Moderate	67716362	58045.83	0.055	0.486	0.431	0.215	0.022
	High	45400560	38916.94	0.147	0.594	0.448	0.239	0.024
	All GVD02	146222594	125340.64	0.051	0.594	0.543	0.220	0.026
GVD03	Low	29504638	25291.10	0.034	0.396	0.361	0.200	0.023
	Moderate	75391711	64625.07	0.041	0.436	0.395	0.209	0.020
	High	30118717	25817.48	0.147	0.516	0.369	0.230	0.020
	All GVD03	135015066	115733.65	0.034	0.516	0.481	0.212	0.024
GVD04	Low	6192746	5308.36	0.066	0.630	0.564	0.206	0.016
	Moderate	34555803	29620.91	0.070	0.670	0.600	0.215	0.019
	High	17789317	15248.84	0.148	0.568	0.420	0.239	0.025
	All GVD04	58537866	50178.11	0.066	0.670	0.604	0.222	0.024
NULo1	Low	9558842	8193.75	0.061	0.546	0.485	0.238	0.024
	Moderate	30242094	25923.24	0.063	0.557	0.494	0.243	0.024
	High	27857950	23879.57	0.147	0.609	0.462	0.250	0.025
	All NULo1	67658886	57996.57	0.061	0.609	0.548	0.245	0.025
CERo1	Low	7234098	6201.00	0.070	0.533	0.464	0.210	0.024
	Moderate	37280435	31956.44	0.071	0.595	0.524	0.219	0.020
	High	59171999	50721.68	0.147	0.662	0.515	0.253	0.031
	All CERo1	103686532	88879.13	0.070	0.662	0.592	0.238	0.032
Western Desert (All IBRA Regions)	Low	165214734	141620.53	0.023	0.630	0.607	0.200	0.026
	Moderate	617842315	529608.66	0.039	0.673	0.634	0.207	0.025
	High	462249472	396235.93	0.146	0.763	0.617	0.236	0.030
	All Classes	1245306521	1067465.12	0.023	0.763	0.740	0.217	0.031

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Chapter 6 Research Findings and Conclusions

The chief aim of this research has been to investigate how remote sensing technologies can improve our understanding of the Aboriginal archaeological record by revealing new information about past land use and resource use behaviours. This theme has been explored in reference to three driving research questions (see Chapter 1), discussed individually below. As a whole, the outcomes of this research suggest that remote sensing has much to offer researchers of Aboriginal archaeology, which is not entirely surprising since remote sensing data have been integrated with other natural science disciplines for decades. However, it is peculiar that in comparison to other regions of the world, Australian archaeology has been comparatively slow to adopt these technologies. It is evident that this attitude is changing, for the better, and hopefully, years from now, this research will join a wave of spatial science and environmental remote sensing innovations in Australian archaeology.

6.1 Q1: IN WHAT CONTEXTS HAS REMOTE SENSING BEEN USED IN AUSTRALIAN ARCHAEOLOGY?

The first research question of this thesis was investigated in Chapter 2, where I presented a comprehensive literature review on the history and use of remote sensing technologies by Australian archaeologists, with particular reference to how aerial and satellite imagery have been used to investigate the Aboriginal archaeological record. The review showed that, as a discipline, Australian archaeology has been using GIS-related technologies and software to investigate the Aboriginal archaeological record for decades, but it has been slow to integrate data and products derived from advanced remote sensing with contemporary research.

From the early years of Australian archaeology and into the 1990s, there has been an dismissive attitude that remote sensing was not applicable to the investigation of the Aboriginal archaeological record because it was expensive, required advanced training and the resolution of image products was not of sufficient resolution to identify site features or archeological objects (Connah and Jones, 1984; Kearns 1989). Accordingly, the discipline has been slow to incorporate environmental remote sensing with archaeological research in Australia. It is true that the high costs of imagery and the technological know-how needed to operate software and analyse data into meaningful information were prohibitive in the early

years. However, since the end of the past century, these factors are no longer hindrances for research. These obstacles have largely been removed through improvements in data accessibility and software, as well as increased awareness of how Earth observation products may be used.

In the past decade, a number of high-profile international publications have featured how remote sensing and Aboriginal archaeological research can be effectively integrated (Bird et al., 2016; Bliege Bird et al., 2008; Kreij et al., 2018). These publications articulate how remote sensing data can contribute to a better understanding of Australia's ancient Aboriginal past and challenge earlier models' perceptions of the archaeological record. In particular, these studies illustrate how remote sensing can reveal behavioural insights into past Aboriginal land use, resource use and human-environment interactions.

Although these works clearly demonstrate that older research attitudes towards remote sensing has shifted, it still seems that there are still few researchers operating in this area of the discipline. I argue that this highlights there is much room for growth and expansion in the use archaeological remote sensing in Australia, and I predict that many articles related to this topic are forthcoming.

6.2 Q2: HOW CAN REMOTE SENSING BE USED TO INVESTIGATE LAND USE AND ARCHAEOLOGICAL SITE DISTRIBUTION IN THE AUSTRALIAN ARID ZONE?

This second research question was explored, in different ways, through the case studies presented in Chapters 3 and 4. Chapter 3 used geomorphometric classification of land units using digital elevation data and Chapter 4 used hyperspectral imagery to discriminate silcrete, an important raw material used for stone artefact manufacture. Although these two studies dealt with different subject matter, Australian geographic settings and methodologies, they both showed how remote sensing can reveal insights into land use and the potential distribution of archaeological sites.

In Chapter 3, satellite-derived data were used to digitally model terrain and reveal that Aboriginal stone arrangements are more commonly constructed in upland contexts of the east Hamersley Ranges (Law et al. 2020). This finding is contrary to official government records, which indicate inland Pilbara stone arrangements were typically constructed in lowland settings like valley floors and plains. Using satellite digital elevation data and geomorphometric techniques, the

processed remote sensing information was combined with geospatial land system data to produce a digital terrain model where topographic land units such as flat plains, hill toeslope, mid-slope, upper hillslope and flat hilltop contexts were objectively classified. When stone arrangement site locations were compared to the digital model, it clearly showed that the true pattern of land use was considerably different from government records, and stone arrangement sites are more likely to be constructed on hilltops and upper slopes of the mountainous ranges.

In Chapter 4, aerial hyperspectral imagery was used to show the distribution of silcrete lag gravels in the Dalhousie Springs area of central Australia (Law et al., 2020). Silcrete was an important natural resource used for stone artefact manufacture in central Australia, and it is the dominant raw material recorded in artefact assemblages from this region of the continent. Silcrete is mostly composed of hydrated silica, a family of quartz minerals which include forms of amorphous, cryptocrystalline and microcrystalline silica. My background research revealed that hydrated silica has a distinctive spectral signature, and rocks, like silcrete, with high quantities of hydrated silica can be discriminated with high resolution hyperspectral imagery.

Using the spectral signature of hydrated silica as a library reference, the signature was matched to pixels in an aerial hyperspectral image, identifying places where hydrated silica dominated the image pixel. The result showed that silcrete is widely distributed in the gibber plain surrounding the Dalhousie Springs complex (Law et al., 2020). This information provides an indication of where Aboriginal people would have been able to procure silcrete. The results are important to predicting where stone artefact quarries may be found in the landscape, and it provides insights into the resource's abundance within the project area, which are not delineated on local geological maps.

Although the methodologies employed and the data used in the Chapter 3 and 4 case studies are different, both studies illustrate how remote sensing data can contribute to a better understanding of land use behaviour and predict where particular archaeological site types are likely to be distributed. These case studies were designed to illustrate the usefulness of remote sensing to Aboriginal archaeology, and by no means do they represent the entirety of possibilities of the applying such technologies to the interpretation of the archaeological record. Much more is possible, but to fully realise the potential, archaeological researchers will need to collaborate with spatial scientists or undertake advanced training.

6.3 Q3: HOW CAN REMOTE SENSING ENHANCE OUR UNDERSTANDING OF ABORIGINAL ECOLOGY AND LAND USE IN THE AUSTRALIAN ARID ZONE

This third and final research question was designed to illustrate how multiple types of remote sensing data can be processed, analysed and integrated with other kinds of geospatial data to create a detailed ecological model of precontact Aboriginal land use the Western Desert (Chapter 5). The model was constructed using various types of ~30m satellite image-derived products that depict access to natural resources in an ideal environmental scenario, based on water abundance, maximum vegetation greenness and terrain ruggedness. The information revealed that there is a wide range of variability amongst suitable foraging habitats in the Western Desert. High-ranked foraging habitats are not necessarily endemic to any particular bioregion or land system, and there is a wide range and uneven distribution of suitable foraging areas within the more broadly classified bioregional areas themselves.

Observing the variability and patchiness of the foraging habitat suitability led to a reconsideration of human-environment interactions and previous ecological models of land-use in the Western Desert. The foraging habitat model challenges perceptions about Aboriginal occupation in arid landforms such as dunefields, and it questions the validity of some past characterisations of some bioregions and land system types (e.g., sandridge desert) as 'barriers' for foraging activities. It shows that there are areas of the Western Desert where unsuitable foraging conditions have likely persisted since the beginning of last glacial cycle, around 30,000 years ago. There are broad areas of with low-ranked suitability, and it is hypothesised that occupation would always have been rare in these impoverished places, with lengthy periods of disuse between occupation events.

Conversely, the high spatial resolution of the model also showed that in the right environmental circumstances, there are areas of the sandridge desert where resources would have been abundant. In some dune field areas, the model suggests that swale areas would have been lush with access to vegetation and water resources. Thus, on a fine-grained ecological scale, some dunefield areas would not have been an impediment to occupation.

One of the greatest strengths of this foraging suitability model is that it is testable with conventional archaeological fieldwork and artefact analysis. There are currently only a handful of places in the Western Desert that have been subject to

comprehensive archaeological investigations (Smith, Williams & Ross, 2017), so spatial models like the one presented in Chapter 5 are likely to be useful to future investigations of this vast region.

6.4 SIGNIFICANCE AND IMPLICATIONS

The research presented in this thesis is amongst the first in Australia to use advanced remote sensing to investigate the Aboriginal archaeological record. Each of the presented case studies advances the archaeological knowledge in their regional setting, so in this very localised sense, the research findings offer much to improve our understanding of the ancient Aboriginal past of these places (see section 6.3). However, from a much broader perspective, the significance of this research has far greater implications for prehistoric archaeology worldwide, as the remote sensing methods utilised in this study can potentially assist archaeological investigations in other arid regions of the world.

One of the greatest strengths that remote sensing offers archaeology is its ability to objectively observe and accurately measure ground phenomena from above and from afar. The data acquired through aerial and satellite remote sensing can be used to reveal landscape patterns that may otherwise be missed through conventional ground-based fieldwork. If sensors are functioning properly, the data is analysed appropriately and the information is geographically comprehensive, consistent and objective, then it is less likely to be affected by human bias or recording error. An example of such an error was presented in the Pilbara stone arrangement case study of Chapter 3, where it was shown that the topographic context of stone arrangements was misrepresented in field recordings filed with West Australian governments (Law et al., 2017). Previous records indicated stone arrangements were located in valley lowlands, but the modelled digital elevation data showed that stone arrangements are predominately constructed on upper hillslopes and hilltops.

Similarly, in the Dalhousie Springs hyperspectral case study presented in Chapter 4, the rock type silcrete does not appear on government geological maps (Law et al., 2020). To some researchers, this would suggest that the silcrete used for artefact manufacture is not available locally; thus, the source of this important economically important raw material must have been procured some distance from the springs complex. However, as the hyperspectral analysis demonstrated, silcrete is abundant, and it is the principal rock material that comprises the stony gibber

plain landscape that surrounds the spring complex. To solely rely on the geological map to determine silcrete provenance would be erroneous in this instance, misrepresenting the true distribution of the raw material.

The methodologies presented in the Pilbara and Dalhousie Springs case studies also have potential to be applied to prehistoric archaeological studies in many other areas of the world, but I believe they will be most useful in arid environmental contexts. The geomorphometric analytical methods that were applied to the digital elevation data in Chapter 3 can also be used to discriminate topographic land units in virtually any region of the globe, and the geomorphometric methods can be applied to most DEMs. In this research, I used ALOS digital elevation data, but it is worth noting that there are other global DEMs available that may be used in the same manner, including NASA's Shuttle Radar Topographic Mission (Rabus et al., 2003) and the ASTER Global Digital Elevation Map (Abrams and Crippen, 2019).

Likewise, the hyperspectral methods presented in Chapter 4 may be integrated with prehistoric stone artefact studies elsewhere in the world, pending hyperspectral imagery is available for the region of interest. Silicified rock types were commonly used to manufacture stone artefacts in many arid regions of the world. As shown here, silicified rocks are rich with hydrated silica, which can be discriminated and mapped in hyperspectral imagery, but there is also scope for use of hyperspectral remote sensing in the detection of a wide range of other surface minerals that may have relevance to understanding the archaeological record. The greatest limitation to hyperspectral studies is acquiring and accessing suitable imagery for an area of interest; however, recent information suggests this is changing, and there are many new hyperspectral imaging satellites on the horizon (Transon et al. 2018). Presently, NASA's Hyperion archive of hyperspectral satellite imagery offers patchy coverage for many of arid areas of the globe, and it is freely available from many agencies online, including the Terrestrial Ecosystem Research Network (TERN) here in Australia (tern.org.au). More promising, however, are the upcoming launches of Germany's EnMap (enmap.org) and NASA's HypIRI satellites (hyspirl.jpl.nasa.gov), which will be equipped with ~30m resolution hyperspectral instruments. These launches are planned between 2020 and 2025, and the hyperspectral images that they produce will have global coverage and be freely available, potentially opening up new avenues of stone artefact provenance research.

Prehistoric hunter-gatherer-foraging peoples that lived in arid regions around the planet share the common trait that their physical footprint on the Earth was comparatively low impact. With the exception of discarded stone tools, there is often little material evidence of their occupation. The limited information makes it challenging to understand how early peoples settled, subsisted and successfully adapted to life in arid places, yet worldwide there are many examples of prehistoric groups occupying these climatically harsh environments. The fact that early peoples adapted and survived in such seemingly harsh places is a testament to the complexity of their socioeconomic systems, despite there being little physical evidence of their existence. Remote sensing has the capacity to reveal much about the environment that desert peoples lived, allowing for inference on how they interacted with natural resources and different land contexts. This thesis makes the argument that remote sensing can make a significant contribution to revealing past land use behaviours, especially in regards to how past foraging peoples interacted with the natural environment itself. Although the foraging habitat suitability model presented in Chapter 5 was tailored to the Australian Western Desert, the principles behind it should be relevant to researchers investigating human-environment interactions in similar arid contexts. The significance of this observation is that it is relevant for not only Australian Aboriginal studies, but for prehistoric archaeology worldwide.

6.5 FUTURE RESEARCH

Undoubtedly, the modern benefits of remote sensing far outweigh any scepticism the technology may have received in the past, and the accessibility of remotely sensed imagery has become more commonplace than ever before. It is fair to observe that this thesis only scratches the surface on the range of potential data types (see Chapter 2) and remote sensing analytical methods that could be useful to Australian archaeological studies (see Chapters 3-5).

I believe that there will be substantial growth in this area of discipline, and there will be an increase in the range and diversity of future remote sensing studies in Australian archaeology. The increasing diversity of analysis-ready Earth observation products, improvements with computer processing power, affordable software and ease of data access have already placed the tools well within the grasp of most researchers, should they be inclined to learn how to use them. The biggest obstacle to growth is likely to be training opportunities and experience with the

application of remotely sensed datasets. It is therefore important that universities look to integrate spatial science training opportunities with Australian archaeological curricula.

Unlike other areas of the world, Australia does not currently have a university-based research centre that is explicitly dedicated to archaeological remote sensing. In Europe and North America, there are research centres and institutes dedicated to the topic. For instance, the Ludwig Boltzmann Institute (<http://archpro.lbg.ac.at>), ArchaeoLandscapes Europe (<http://www.arcland.eu>), the University of Birmingham (<http://www.vista.bham.ac.uk>) and the University of Arkansas (<http://cast.uark.edu/home/research.html>) offer preeminent training and research opportunities in the field of archaeological remote sensing, spatial science and virtual archaeology. Thus, considering the interest overseas, it is not unreasonable to consider that a centre or institute dedicated to archaeological remote sensing may someday be feasible in this country.

In the meantime, I expect that the future of Australian archaeological remote sensing will involve substantial interdisciplinary collaboration. It is natural that this topic will attract the attention of many academic communities (e.g., history, geology, palaeoecology, and Quaternary science) that have interests in better understanding the continent's Aboriginal past. However, it is possible that the greatest collaborations in the future will be with Aboriginal communities, exploring how remote sensing may be integrated with Traditional Owner perspectives, values and questions about the past.

6.6 CONCLUDING REMARKS

Possibly the single most important and practical lesson that I learned during the course of my research is that high spatial and spectral resolution data are not absolutely necessarily for most landscape-focused projects or ecologically-themed archaeological projects. For these kinds of studies, medium resolution imagery (~30m pixel) is sufficient (see Table 2-1). This observation does not disregard the importance and usefulness of high resolution products. There is clearly a place for high spatial and spectral resolution imagery, and such data is entirely appropriate for some archaeological contexts (e.g., Chapter 4). However, at present these kinds of products are quite costly and require greater computing power. Technological improvements will undoubtedly reduce such research impediments in the future, but for the time being, there is considerable scope for archaeological investigators

to take advantage of the abundant medium resolution datasets that are currently available.

I conclude this thesis with some general thoughts about the knowledge gap that exists between remote sensing science and archaeology. It is time for Australian archaeological research to move far beyond its past dogmatic position that the sole use for satellite and aerial imagery is for capturing simple overviews of archaeological sites. A more practical and productive approach is to analytically explore the rich spectral, spatial and temporal information captured in remote sensing data and learn how to better harness this powerful technology to investigate the Aboriginal past. Given the nature of the Aboriginal archaeological record, it is unlikely that remote sensing will be used in exactly the same manner as it is in archaeological studies elsewhere in world, which is preoccupied with discriminating architectural features, culturally modified landforms and archaeological objects. Australian archaeologists must be creative with how remote sensing technologies are used to investigate the Aboriginal archaeological record, looking towards other natural science disciplines such as ecology, biology, geology and environmental science for inspiration. This will help researchers continue to develop and innovate novel approaches for investigating and learning more about the continent's ancient Aboriginal past.

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Appendix A – PhD Publication 1

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Digital Terrain Analysis Reveals New Insights into the Topographic Context of Australian Aboriginal Stone Arrangements

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ABSTRACT Satellite-derived surface elevation models are an important resource for landscape archaeological studies. Digital elevation data is useful for classifying land features, characterizing terrain morphology, and discriminating the geomorphic context of archaeological phenomena. This paper shows how remotely sensed elevation data obtained from the Japan Aerospace Exploration Agency's Advanced Land Observing Satellite was integrated with local land system spatial data to digitally classify the topographic slope position of seven broad land classes. The motivation of our research was to employ an objective method that would allow researchers to geomorphometrically discriminate the topographic context of Aboriginal stone arrangements, an important archaeological site type in the Pilbara region of northwest Australia. The resulting digital terrain model demonstrates that stone arrangement sites are strongly correlated with upper topographic land features, a finding that contradicts previous site recordings and fundamentally changes our understanding of where stone arrangement sites are likely to have been constructed. The outcome of this research provides investigators with a stronger foundation for testing hypotheses and developing archaeological models. To some degree, our results also hint at the possible functions of stone arrangements, which have largely remained enigmatic to researchers. © 2017 The Authors. *Archaeological Prospection* Published by John Wiley & Sons Ltd.

Key words: Australian Aboriginal archaeology; stone arrangement; Advanced Land Observing Satellite (ALOS); geomorphometry; topographic position index; digital elevation model (DEM)

Introduction

Documenting and understanding the context of archaeological sites in relation to surrounding terrain features is essential to landscape archaeological studies worldwide (De Reu *et al.*, 2013; De Reu *et al.*, 2011; Turrero *et al.*, 2013). Satellite-derived digital elevation data offer the modern archaeologist a powerful information platform for the analysis and modelling of land surfaces (Hritz, 2014; Keay *et al.*, 2014; Lasaponara and Masini, 2011, 2012; Parcak, 2009; Wiseman and El-Baz,

2007). Remotely sensed digital elevation models (DEMs) and digital surface models (DSMs) are useful datasets for investigating the distribution of archaeological sites in a broad landscape context, giving researchers the ability to classify and model terrains with greater accuracy and less subjectivity than traditional field methods.

The effectiveness of this approach is exemplified in our research of Aboriginal stone arrangement sites from the Banjima Native Title Claim Area, located in the Pilbara region of northwest Australia (Figure 1). Although stone arrangement sites are found throughout Australia, few studies have identified the site densities noted for the inland Pilbara, and in particular, the Packsaddle Valley area of the central Hamersley Plateau (Hook, 1999; Hook and Di Lello, 2010; Hook *et al.*, 2010; Hook *et al.*, 2002; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b) (Figure 1). It is unclear if

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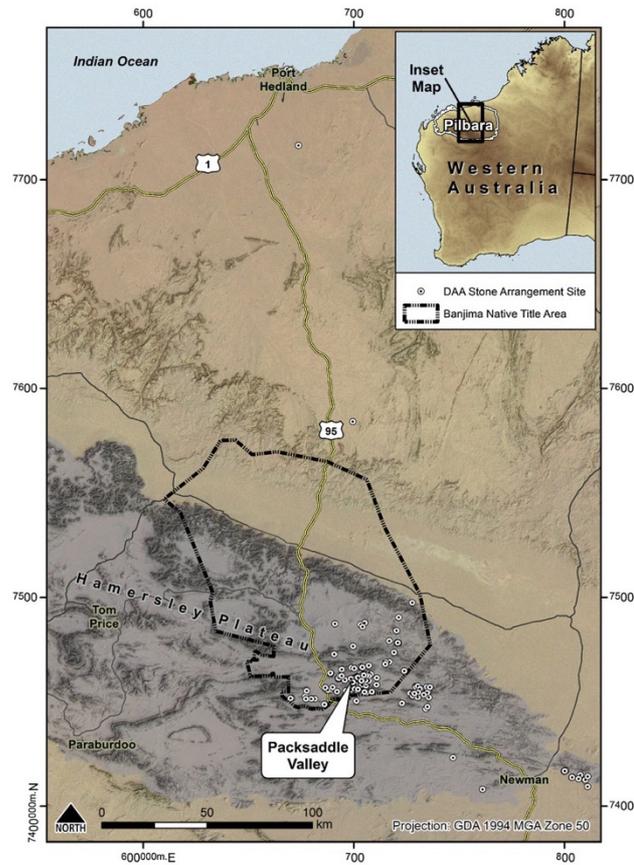


Figure 1. Regional overview map with major geographic features, Department of Aboriginal Affairs (DAA) registered stone arrangement sites, cultural areas, and the approximate position of the Packsaddle Valley, Pilbara region of Western Australia. [Colour figure can be viewed at wileyonlinelibrary.com]

the high frequency of Packsaddle Valley stone arrangement sites is due to ancient cultural behaviours or if it is a product of survey coverage, as much of the area has been intensively surveyed for proposed mining development. Regardless of site numbers, it is well known that stone arrangements are culturally significant to the contemporary Aboriginal groups, and investigators are intrigued by their enigmatic function and curious concentration in the Packsaddle Valley area (Hook, 1999; Hook and Di Lello, 2010; Hook *et al.*, 2010; Hook *et al.*, 2002; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b).

Previous research has shown that there is conflicting information on the topographic context of Packsaddle Valley stone arrangements. Archaeological site records from the Western Australian Department of Aboriginal Affairs (DAA) indicate that Packsaddle Valley stone arrangements most often occupy lower topographic landforms such as stony plains, valley floors, and lower hillslopes (Hook *et al.*, 2010). More recently, investigators have observed that officially registered site details such as the topographic and geomorphological setting are frequently inaccurate and vulnerable to subjective or inconsistent field assessments (Law,

2014a, 2014b). The consequence of erroneous recording is a skewed distributional pattern that suggests stone arrangements more frequently occur in lower topographic land units. New survey data, including site revisits, suggests that stone arrangements are more likely to be constructed on hilltops and hillslopes (Law, 2014b); however, the latest information is based on a limited sample of 26 sites in a localized area and may not be representative of a regional pattern.

One of the greatest implications of the conflicting information is that archaeologists, land managers, policy-makers, and Aboriginal stakeholders are inadequately guided in their research and conservation decisions. Simply put, if the geomorphic context and topographic distribution of stone arrangements cannot be characterized, then it is difficult to effectively protect sites, manage lands, and conserve areas where unrecorded stone arrangements may exist.

Our research aims to resolve the question of where stone arrangement sites are distributed in the Packsaddle Valley area by using satellite-derived DEMs and digital land system data. Although the archaeological subject matter of this study is uniquely Australian, the principles and methods espoused herein are applicable to all researchers interested in using digital elevation data to model archaeological site distribution and terrain features.

The Packsaddle Valley study area

Environmental setting

The Packsaddle Valley is in the Pilbara biogeographic region, an arid rangeland environment receiving an average of 322 mm rainfall annually (Bureau of Meteorology, 2016). Rainfall is largely correlated with summer cyclone events, and average rainfall is rarely attained without the contribution of cyclonic activity. The Packsaddle Valley extends along an east–west corridor, dissecting the North Flank and Packsaddle Ranges (Figure 2). The study area of 364.4 km² is roughly framed by the Great Northern Highway on the west, the Banjima Native Title Claim boundary on the south, and various government land parcel boundaries on the north and east (Figure 2).

The Department of Agriculture and Food, Western Australia (DAFWA) has defined and mapped five dominant land systems in the Packsaddle Valley area. For this study, these land systems are broadly divided into upland or lowland classes, based on their topographic relief and land features (Table 1 and Figure 2). The Newman Land System is the only upland land

system, occupying 65.8% of the study area. It includes plateaux, ridges, and mountains with relief of up to 450 m (Payne, 2004). Prominent land features include exposed ridges, vertical escarpments, and weathered hilltops with skeletal soils. Deep gullies dissect much of the Newman land surface, exposing the layered and sometimes folded bedding of Proterozoic-age banded ironstone (Trendall *et al.*, 1998).

Topographically below the Newman Land System are the Boolgeeda, Pindering, Platform, and Wannamunna Land Systems (Table 1). Together, these lowland land systems occupy 34.2% of the study area. Topographic relief varies from 5 m to 30 m in these lower land systems. They are depositional environments, characterized by Quaternary colluvium and detrital ironstone gravels, and commonly referred to as ‘stony plains’ (Payne, 2004).

Stone arrangements

Australian Aboriginal stone arrangements are a well-known archaeological site type documented throughout Australia. Horton (1994: 1029) points out that stone arrangements have been recorded in a wide range of forms, including ‘cairns, mounds, walls, lines, circles, crescents, loops, spirals, “horseshoes” and rock-lined pits.’ It has been further emphasized by Rowland and Ulm (2011) that fish traps and weirs are additional Aboriginal stone arrangement types with widespread continental distribution.

In Western Australia, the *Aboriginal Heritage Act 1972* defines stone arrangements as a ‘man-made structure’ distinguished by ‘the placement or arrangement, by Aboriginal people, of stone, wood or other material into a structure for ceremonial or utilitarian purposes.’ In this study, the term ‘stone arrangement’ is used to describe a group of standing stones that have been positioned in a non-random pattern across an open land surface. Although single, isolated embedded stones are often reported as stone arrangements, single stone sites are not included in our research due to the possibility that a stone may have been uplifted via natural processes (e.g. tree roots or erosion) (Law, 2014a, 2014b).

A remarkably high number of Aboriginal stone arrangement sites have been documented in the central Hamersley Plateau, which includes Packsaddle Valley area. The concentration of stone arrangement sites in the central plateau region is far greater than any other area of the Pilbara, with more than 180 sites reported (Figure 1). Undoubtedly the high frequency of documented sites is the result of intense archaeological

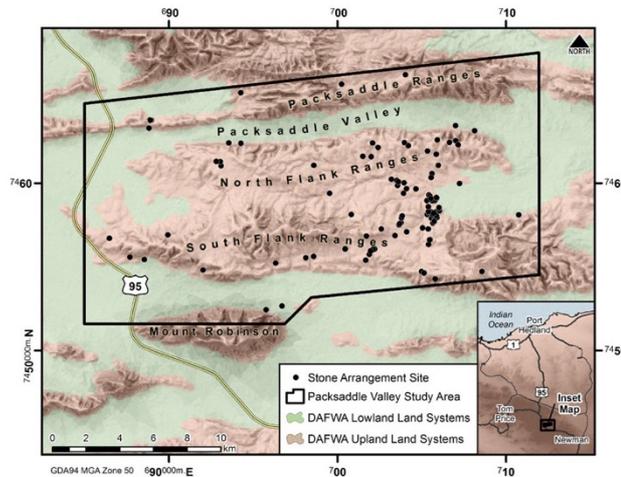


Figure 2. Packsaddle Valley study area map and land system classes, including locations of stone arrangement sites. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1. Packsaddle Valley study area land system descriptions (after Van Vreeswyk *et al.*, 2004).

Land system	Class	Description	Land area (km ²)	Percentage of study area (%)
Boolgeeda	Lowland	Dissected slopes and raised plains supporting hard spinifex grasslands. Topographic relief up to 20 m.	92.5	25.4
Newman	Upland	Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands. Topographic relief up to 450 m.	239.6	65.8
Pindering	Lowland	Gravelly hardpan plains supporting groved mulga shrublands with hard and soft spinifex. Topographic relief up to 10 m.	6.9	1.9
Platform	Lowland	Dissected slopes and raised plains below ranges supporting hard spinifex grasslands. Topographic relief up to 30 m.	11.4	3.1
Wannamunna	Lowland	Hardpan plains and internal drainage tracts supporting mulga shrublands and woodlands. Topographic relief up to 5 m.	14.0	3.8

survey coverage, as much of the area has been thoroughly surveyed for mining developments. Nonetheless, it is additionally plausible that the high density of stone arrangement constructions may be due to ancient Aboriginal cultural behaviours yet to be understood.

Approximately 95% of the Packsaddle Valley study area has been subject to pedestrian archaeological survey, resulting in a large sample of recorded stone arrangement sites. According to heritage site records, there are 104 undisturbed stone arrangement sites in the current study area (Figure 2). These sites are in their natural landform context and have not been impacted by mining or other industrial activities.

Previous research indicates that nearly all Packsaddle Valley stone arrangements are constructed from banded ironstone or ironstone conglomerate, often with lateritic or pisolitic gravels (Hook, 1999; Hook and Di Lello, 2010; Hook *et al.*, 2010; Law, 2014a, 2014b; Quartermaine, 1996a, 1996b). Stone arrangements are normally constructed on relatively level ground surfaces, with the principal construction method involving the burial and upright vertical embedment of a stone. Occasionally, a stone may be positioned and placed atop of the ground.

Researchers further report that the maximum height of most embedded stones range 25–45 cm above

ground surface, with the buried base of embedded stones ranging 10–20 cm below surface (Hook and Di Lello, 2010: 291). A previous review of stone arrangement records found that a typical stone arrangement site contains an average of 34 stones (Hook *et al.*, 2010); however a recent desktop study, with a larger sample of site records, estimates an average of 23 stones per arrangement (Law, 2014a). Sites constructed with hundreds of stones, although uncommon, are also reported (Hook and Di Lello, 2010: 291; Hook *et al.*, 2010).

Linear and curvilinear designs of stone arrangements are the most common regionally (Figure 3); however, amorphous designs and cairns also occur (Figure 3). Positioned stones have been documented as spanning a few metres, or they can potentially stretch to more than 100 m in total length (Hook *et al.*, 2010). In the latter instances, the stone arrangement may involve hundreds of embedded stones (Hook and Di Lello, 2010; Hook *et al.*, 2010; Hook *et al.*, 2002; Quartermaine, 1996a, 1996b). There are no examples of any stones having been physically modified in the construction of arrangements in Packsaddle Valley area.

The precise antiquity and function of stone arrangements is poorly understood. Preliminary optically stimulated luminescence dates suggest most stone arrangements were constructed in the past 300 years;

however further analysis is recommended (Hook and Di Lello, 2010; Hook *et al.*, 2010). Ethnographic data is often cited to imply function, leading many archaeologists to speculate that stone arrangements were constructed for ceremonial and mythological purposes, although utilitarian functions are also possible in some instances (Gould, 1969; Hook and Di Lello, 2010; Law, 2014a, 2014b; Quartermaine, 1996a).

Materials and methods

The georeferenced locations of 104 stone arrangement sites in the Packsaddle Valley study area were used in this study. The two key information sources used to produce the digital terrain model were: (1) the one arc-second Advanced Land Observation Satellite (ALOS) Global World 3D – 30 m (AW3D30) DSM dataset and (2) the DAFWA Pilbara Land Systems spatial data. ESRI's ArcGIS 10.3 with the Spatial Analyst extension was used to analyse all spatial and remote sensing data associated with this research.

The AW3D30 DSM dataset is a free raster product available from the ©JAXA Earth Observation Research Centre web portal (<http://www.eorc.jaxa.jp/ALOS/en/aw3d30/>). It is based on elevation data acquired via the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM), a sensor mounted aboard



Figure 3. Examples of Packsaddle Valley stone arrangement design types. Generalized design categories include (a) linear, (b) curvilinear, (c) amorphous, and (d) cairn (Photographs: J. Brindley). Variations in design type categories are common regionally. [Colour figure can be viewed at wileyonlinelibrary.com]

the ALOS during its mission between 2006 and 2011. The AW3D30 DSM dataset has been post-processed and vertically corrected against JAXA's high resolution 5 m mesh DSM of the ALOS World 3D Topographic Data (Iadono *et al.*, 2014; Takaku *et al.*, 2014). The resulting AW3D30 DSM dataset offers ± 5 m vertical height accuracy, making it amongst the most accurate elevation datasets available at 30 m horizontal resolution. Thus, it is a spatially averaged product of the combined 30 m DSM and 5 m DSM ALOS datasets. Although it is a DSM product and does not exclusively represent bare-earth elevation data, the DSM measurements have negligible effect on our study because of the lack of tall or dense tree canopies and buildings in the study area. The local arid environment precludes the growth of a significant vegetation overstorey that could obscure satellite measurements, and there are few building structures in the study area. Still, to minimize elevation irregularities, the AW3D30 DSM data was further processed using a mean focal statistics filter (90 m circular radius) to reduce image noise and smooth vegetation/land surface features. We additionally omitted the industrial zone from the AW3D30 DSM dataset to ensure mining infrastructure and altered ground surfaces did not affect the classification results.

The DAFWA digital land systems data is the second set of spatial information used in the digital terrain model. The DAFWA data corresponds with an encyclopaedic environmental study of the Pilbara biogeographic region (Van Vreeswyk *et al.*, 2004). Pilbara land system maps can be viewed at the DAFWA web portal (<https://www.agric.wa.gov.au/maps-and-data>), and the spatial data is available to researchers under licensed agreement with the state government. It is a vector-based dataset, containing the spatial boundaries and descriptions for the Pilbara land system classes as defined by Van Vreeswyk *et al.* (2004).

A number of geomorphometric classification methods have been proposed to discriminate topographic slope position and digitally classify land surfaces (e.g. De Reu *et al.*, 2013; Deumlich *et al.*, 2010; Iwahashi and Pike, 2007; Miller and Schaetzl, 2015; Riley *et al.*, 1999; Weiss, 2001). This project adopts the classification methodology espoused by Deumlich *et al.* (2010) and utilizes the ArcGIS Relief Analysis toolbox extension developed by Miller (2015) to construct the topographic slope position model.

The two variables used to categorize land surfaces into their respective topographic slope position class are the Topographic Position Index (TPI) and slope gradient (in degrees). These variables were calculated in ArcGIS using the AW3D30 DSM mesh grid

elevation values. A circular neighbourhood radius of 120 m was used in the calculation of the TPI values, and the slope gradient was computed for each individual grid cell. The measured TPI and slope gradient values were saved as separate raster files and entered as independent variables in the digital classification of the topographic slope position, discussed later.

Miller's (2015) Relief Analysis toolbox was used to digitally categorize the TPI and slope gradient values into the topographic slope position classes designated by Deumlich *et al.* (2010) (Table 2). For our study, we replaced the term 'valley' with 'gully or scree slope' to better reflect local Pilbara land features. Another significant difference with the Deumlich *et al.* (2010) method is the use of digital land system data to topographically differentiate flat upland surfaces (Class 4) and flat lowland surfaces (Class 5) classes (Table 2). This was achieved using the DAFWA land system polygons as a grid cell extraction and reclassification mask in the final stage of the analysis. Thus, the digital land system data functioned to delineate and reclassify the topographic slope position of flat ground surfaces in upland land systems from flat surfaces in lowland land systems (Figure 2).

The 'flat surface' class is a potentially problematic category to classify with the algorithm, as the equation does not differentiate the topographic context of 'flat surfaces.' For example, the algorithm classifies the topographic slope position of a flat stony plain in the same manner as a flat hilltop land surface. The 'flat surface' class can thereby be misleading if the topography cannot be discriminated. The DAFWA digital land systems data resolves this potentially problematic scenario, allowing for 'flat upland surface' and 'flat lowland surface' slope classes to be distinguished. The 'flat upland surface' class is interpreted to be broadly flat hilltop or hillslope areas, mesas, and other relatively level upland ground surfaces. Stony plains and alluvial flats are considered to be 'flat lowland surfaces' that are topographically below upland land systems.

With the digital terrain model complete, the final stage of the analysis compared the Packsaddle Valley stone arrangement site locations with the modelled topographic slope position classes. ArcGIS was used to calculate land area (in square kilometres) for each topographic slope position class and extract the topographic slope position class values for each georeferenced stone arrangement site centroid ($n = 104$). As outlined by Kvamme (1997), a Chi-square goodness-of-fit statistical analysis was used to test the non-random nature of the stone arrangement spatial patterning. The goodness-of-fit statistical method

Table 2. Topographic slope position classification criteria.

Class	Description	Topographic Position Index	Slope (deg)	Land system
1	Summit, hilltop, ridge	> 1	—	—
2	Upper slope	> 0.5 ... ≤ 1	—	—
3	Midslope	> -0.5 ... < 0.5	> 2	—
4	Flat upland surface	∓ -0.5 ... ≤ 0.5	≤ 2	DAFWA Upland Land System Mask
5	Flat lowland surface	∓ -0.5 ... ≤ 0.5	≤ 2	DAFWA Lowland Land System Mask
6	Lower slope	∓ -1 ... ≤ 0.5	—	—
7	Gully, scree slope	< -1	—	—

cross-tabulates the observed and expected stone arrangement sites frequencies against topographic slope position classes, thus testing the null hypothesis that stone arrangement sites are evenly distributed across all classified land units. In addition to this Chi-square test, a simple site frequency ratio was calculated comparing observed and expected number of stone arrangements. It enables a meaningful comparison of stone arrangement distribution for each topographic slope position class regardless of land area size.

Results

The resulting digital terrain model of topographic slope position classes, with stone arrangement site locations is presented in Figure 4. Figure 4 demonstrates that stone arrangement locations are highly correlated with upper topographic slope positions. The extracted raster values presented in Table 3 indicate 85.6% of

Table 3. Frequency statistics of Packsaddle Valley stone arrangements by topographic slope position class and study region land area.

Topographic slope position class	Stone arrangement (n)	Stone arrangement (%)	Land area (km ²)	Land area (%)
Flat lowland surface	2	1.9	88.4	24.3
Gully, scree slope	10	9.6	64.9	17.8
Lower slope	3	2.9	28.9	7.9
Midslope	16	15.4	49.5	13.6
Flat upland surface	16	15.4	16.8	4.6
Upper slope	17	16.3	26.0	7.1
Summit, hilltop, ridge	40	38.5	74.8	20.5
Industrial zone ^a	0	0.0	15.1	4.1
Total	104	100	364.4	100

^aLand redevelopments preclude definitive classification due to infrastructure and altered natural ground surfaces.

stone arrangement sites occur in upper topographic contexts, with stone arrangements observed on the summit/hilltop/ridges (38.5%), upper slopes (16.3%), midslopes (15.4%), and flat upland ground surfaces

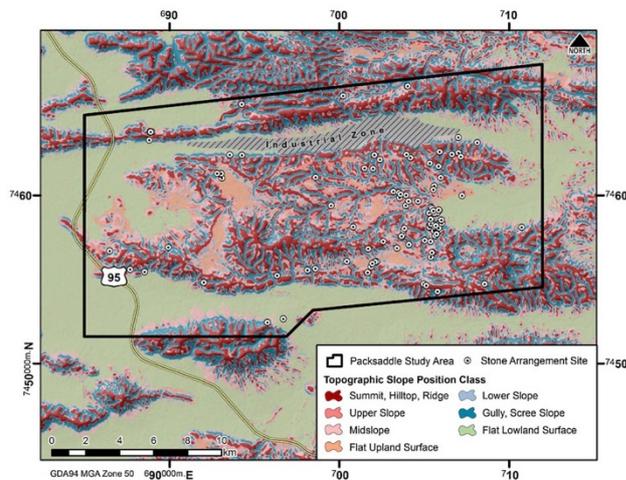


Figure 4. Topographic slope position classes for the Packsaddle Valley study area.

Table 4. Observed and expected site frequency and ratio statistics for Packsaddle Valley stone arrangements by topographic slope position class and study region land area.

Topographic slope position class	Land area ^a (%)	Observed (O) sites	Expected (E) sites	Ratio O/E
Flat lowland surface	25.3	2	26	0.08
Gully, scree slope	18.6	10	19	0.53
Lower slope	8.3	3	9	0.33
Midslope	14.2	16	15	1.07
Flat upland surface	4.8	16	5	3.20
Upper slope	7.4	17	8	2.13
Summit, hilltop, ridge	21.4	40	22	1.82
Total	100	104	104	—

^aNote the total classified land area is 349.3 km², as the industrial zone in Table 3 precludes classification of 15.1 km².

(15.4%) on hilltop and hillslopes. Stone arrangements were observed less frequently in lower topographic settings such as gullies (9.6%), lower slopes (2.9%), and flat lowland surfaces (1.9%) like stony plains (Table 3).

This spatial pattern is not random, and it is not the result of over-representation of any particular topographic slope position class in the study area. The Chi-square goodness-of-fit test performed against the observed and expected site values in Table 4 determined that stone arrangement sites are not equally distributed across all topographic slope position classes, χ^2 (6, $N = 208$) = 79.536, $p < 0.001$. The results further suggest that Packsaddle Valley stone arrangements are more likely to be constructed on upper topographic contexts. This observation is best articulated in the Table 4 site frequency ratio column. The ratios indicate that stone arrangements are most likely to occur on flat upland surfaces (3.20), followed by upper slopes (2.13), summit/hilltop/ridge (1.82), and midslope classes (1.07) (Table 4). In comparison, lower topographic contexts are far less likely to have stone arrangement constructions, with lower slopes (0.33), gully scree slopes (0.53), and flat lowland surfaces (0.08) having comparatively low ratio values (Table 4).

Discussion

Stone arrangements in the Packsaddle Valley have been investigated and recorded by numerous field archaeologists over the past three decades, each with variable expertise in geomorphology. Consequently, some government site records have been lodged with erroneous or misconstrued topographic setting assessments, and in many instances, previous investigators have not used any standardized geomorphic classification system. The variable quality of past recordings has

led to a skewed understanding of where stone arrangements occur in the landscape.

Official site records lodged with the DAA indicate that stone arrangements may be constructed on any geomorphic land unit; however, a review of 73 DAA records by Hook *et al.* (2010: 29–31, 36–37) revealed that Packsaddle Valley stone arrangements are most often reported in lower topographic settings such as valley plains ($n = 23$, 31.5%) and hill bases ($n = 19$, 26.0%). Their contracted study also reports that some stone arrangements have been constructed on low rises ($n = 3$, 4.1%), presumably in lowland settings, although the DAA records do not specify. Hook *et al.* (2010) further document that a small proportion of stone arrangements occur on upland hillslopes ($n = 12$, 16.4%) and ridges ($n = 11$, 15.1%). A small percentage of government records ($n = 5$, 6.8%) lacked any information on the topographic location of stone arrangements (Hook *et al.*, 2010).

More recently, a desktop study was commissioned for the purpose of synthesizing all available site details on stone arrangements in the greater Packsaddle Valley region (Law, 2014a). The study produced a large database of site records ($n = 108$) in the vicinity of our study area. The database includes original DAA files and unpublished material submitted by several consultants between 2010 and 2014. In total, 92 site descriptions contained sufficient information to topographically classify stone arrangements, but the study findings were significantly different to previous research. The records indicated that stone arrangements are more common on upper topographic settings, a stark contrast to the Hook *et al.* (2010) record review. Law's (2014a: 42–46) collation of previously documented site details indicated that the majority of stone arrangements occur in hilltop/ridges ($n = 46$, 50.0%), followed by hillslopes ($n = 13$, 14.1%), toeslopes ($n = 6$, 6.5%), plains ($n = 13$, 14.1%), and terraces ($n = 14$, 15.2%). Law (2014a) attributed the contrary results to a larger site record sample size, the availability of more recently updated site information, observer-recorder biases, variability in geomorphic expertise, and erroneous stone arrangement identification (e.g. natural erosion or tree uplifted rock).

Our study resolves the contradictory findings of earlier reviews, and we argue that digital terrain models are a more objective and accurate representation of topographic context. For the Packsaddle Valley land surfaces, geomorphometric analysis supersedes previous assessments of site topography. The digital terrain model is not impeded by the subjective field observations of multiple site recorders, offering a more consistent approach for determining the topographic

slope position of stone arrangements. It unambiguously demonstrates that stone arrangements are more likely to be constructed in upper topographic land surfaces, resolving the contrasting patterns reported by previous researchers and contributing to greater understanding of stone arrangement spatial patterns in the Packsaddle Valley region.

Future heritage surveys will benefit in the knowledge that Packsaddle Valley stone arrangements are most likely to be constructed on flat upland ground surfaces, followed by upper slopes, summit/hilltop/ridges, and midslopes (Table 4). This information will give researchers better grounding for developing and testing hypotheses and landscape archaeology models. Land managers will be able to make more informed heritage decisions, and Aboriginal stakeholders may corroborate this information with their traditional knowledge to advise policy-makers on conservation issues. Furthermore, our digital terrain model is also a significant step towards developing a predictive model for investigating stone arrangement distribution regionally, particularly in unsurveyed areas.

This research may also improve our insights on the range of possible functions and human behaviours associated with the Packsaddle Valley stone arrangements. For instance, could it be that stone arrangements are common in uplands due to the practicalities of construction? Larger stones are easier to procure in uplands, and ironstone slabs are abundant due to frequent bedrock exposures. It is far easier to construct stone arrangements nearer to the raw material source. In comparison, it would require considerable energy and commitment to transport stones weighing more than 20 kg long distances onto plains and similarly low topographic settings. Traditional Aboriginal hunter-gatherer societies were highly mobile by nature and tended to optimize transport costs. Moving heavy stones long distances to construct arrangements would not seem in character with traditional mobility practices.

Pragmatic behaviours aside, is there a cultural motivation for why stone arrangements are concentrated in upper topographic settings? Many of the sites are positioned on land surfaces with breathtaking views of the surrounding landscape, giving stone arrangements a monumental quality. Admittedly, this observation is an aesthetic attribute that cannot be impartially quantified; however, there is ethnoarchaeological and anthropological evidence that suggests some stone arrangements functioned as totemic or mythological monuments. Could it be that the selected topographic setting of some sites is related to this function?

Gould's (1969, 1980) ethnoarchaeological research with the Nyatunyatjara people of Western Australia's Gibson Desert indicates that some stone arrangements may have totemic mythological significance. Gould (1969: 144) enquired with many Aboriginal elders on the function of a 'serpentine-shaped' arrangement, concluding that 'Rock alignments and artificial rockpiles are consistently interpreted as the bodies or paraphernalia of totemic beings changed by themselves into lithic form.'

If Gould's assessment transcends Aboriginal cultural boundaries, then perhaps some of the Packsaddle Valley stone arrangements functioned as totems or mythological monuments, and their elevated position in the landscape may be related to this function. Local anthropological research by Palmer (1977) deduced that several Packsaddle Valley stone arrangements are mythological sites, related to the Dreamtime movements of a mythological spirit being. Thus, based on this information, it does not seem unreasonable that the topographic context of some stone arrangement sites is related to their monumental function. This hypothesis is admittedly founded on anecdotal evidence, but we believe that the data are compelling enough to warrant further research. In the least, this research does highlight that the spatial sciences have an important role to play in future studies of ancient Aboriginal stone arrangements.

Although the range of possible functions for Packsaddle Valley stone arrangements remains enigmatic, our study on the topographic distribution of stone arrangements is a crucial first step for understanding where stone arrangements occur in the local landscape. This baseline information will undoubtedly contribute to future research of this unique class of Aboriginal cultural phenomena.

Conclusions

Although this example focuses on Australian subject matter, our research methods have applicability to practitioners of landscape archaeology worldwide, especially in regards to site distribution studies. Satellite-derived elevation models and digital land system data are increasingly accessible to archaeologists at no cost, enabling researchers to create custom digital terrain models of virtually any landscape on Earth. In this example, we have demonstrated how digital elevation data and land systems information can be used to discriminate the topographic setting of Packsaddle Valley Aboriginal stone arrangements. Contrary to previous site records, we have established that

Aboriginal stone arrangements are generally constructed in upper topographic contexts. We have speculated that the reason for this pattern is possibly due to the practicalities of resource distribution or perhaps due to unknown ancient totemic or mythological purpose. Other utilitarian functions of stone arrangements are also plausible and likely, but additional research in this area is required.

The Packsaddle Valley digital terrain model is a more objective representation of the topographic context of land surfaces, and our digital classification method more objective and consistent than the varied field observations of past site recorders. Despite the fact that we do not conclusively understand the function of stone arrangements, this research has proved worthwhile in demonstrating that we do understand much about their distribution in the landscape. Future predictive modelling studies will invariably benefit from the spatial patterns revealed in this study.

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Author contributions

In collaboration with BHPBIO and the Banjima Native Title Claimants, M.J.S. and W.B.L. conceived the research project and supervised fieldwork; W.B.L. conducted the background research, designed the

methodology, and performed the spatial analysis; W.B.L. wrote the paper and prepared the figures and tables; M.J.S. contributed to the interpretation and discussion of the results. M.M.L. provided technical and stylistic edits and contributed to the document organization, structure, and statistics. B.O. offered additional technical edits and advised on the geospatial and statistical methods employed in this document.

Declaration of interest statement

The authors declare no conflict of interest.

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Appendix B – PhD Publication 2

Law, W. B., Lewis, M. M., Ostendorf, B., & Hiscock, P. (2020). Reflecting on siliceous rocks in central Australia: Using advanced remote sensing to map ancient “tool-stone” resources. *Geoarchaeology*, 35(3), 400-415.

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LIBRARY NOTE: This appendix has been removed, can be accessed at DOI. Unpublished version can be accessed at Ch.4, pages 63-89 of the thesis.