A NEW FOCUS ON ANCIENT ART: Digital Techniques to Record and Understand Rock Art.

By

Jarrad Kowlessar

Masters of Maritime Archaeology
Graduate Certificate in Screen and Media Production
Bachelor of Applied Geographic Information Systems (Honours)

Thesis
Submitted to Flinders University
for the Degree of
Doctor of Philosophy

The College of Humanities, Arts and Social Sciences
10th March 2023

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ABSTRACT

Rock art as a material cultural artefact, presents significant and unique challenges to all aspects of archaeological analysis and cultural heritage management, including site management issues, preservation methods, and disaster planning against the ever-increasing threats of climate change and industrial destruction.

Although much work has been done towards studying and managing rock art from various viewpoints, a holistic approach encompassing the many requirements, perspectives and outcomes is lacking. This thesis addresses that need by presenting new digital approaches that embrace emerging modern technological applications to offer fresh opportunities that overcome many of the previous barriers to engagement. Applying and demonstrating new methodologies from raw data collection, through cutting edge digital, geospatial and geophysical landscape analysis, this work provides an advanced, but cost-effective new means of gathering, analysing and communicating this information using various platforms.

Firstly, ground-based photography is used to create high-resolution, georectified three-dimensional models of rock art sites, while aerial remote sensing is used to generate models of the landscape around a target site. This reveals a complex Pleistocene landscape, which offers the potential to locate additional archaeological sites and so reveal more about the lifeways of the earliest Australians.

Additionally, this research conducts a new approach to stylistic motif analysis, the first ever machine learning analysis of Australian rock art, using data efficient transfer learning to identify distinguishing features within styles of rock art. By generating a stylistic chronology, it is shown that the model is sensitive to both temporal and spatial patterns in the distribution of rock art in the Arnhem Land Plateau region.

Further, building from thesis site recordings, motif analysis and palaeogeographic reconstructions, a Geographic Information Systems based spatial analysis is produced, applying detailed models to the spatial analysis of rock art site placement. The resultant elevation, land cover and visibility modelling reveal significant changes in the site placement strategies of the rock art in the region, highlighting changes in four key phases of the past environmental history, spanning from the late Pleistocene to the late Holocene.

Finally, this thesis develops a new approach to archaeological landscape visualisation through the use of game engine technology designed for detailed virtual reality immersion. This combines the separate data and archaeological models produced throughout the thesis and merges these into one holistic, virtual cultural landscape simulation that can be dynamically explored and interacted with. The resulting new workflow used to create this simulation makes a unique way for archaeological information to be explored and communicated and is especially useful in communicating complex landscape information in an intuitive way.

This research contributes innovative digital methods to each component of rock art analysis in a structured way that allows data to build constructively towards a unified model of an archaeological rock art landscape. Each section of the thesis research has contributed to detailed and unique knowledge about the rock art of Arnhem Land and together forms a cohesive approach that can be applied to the global discipline of rock art management and analysis.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university

2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and

3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed..

Date...........23/10/2022.........................

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Senior Traditional Owners Alfred Nayinggul and Dudley Lawrence for welcoming me to their country and allowing me to visit and record their cultural heritage for use in this research. Your knowledge, guidance and support on country has allowed this research to occur.

I would like to acknowledge and thank my supervisory panel: Ian Moffat, Daryl Wesley, Liam Brady and Mick Morrison. I would like to thank Daryl Wesley for taking me on countless adventures over the course of my PhD. You have provided immense support, guidance and encouragement and allowed me to achieve everything I have set out to and more. I would like to thank Ian Moffat for the constant support and guidance throughout my PhD, I would not have been able to achieve this without you. I am especially grateful for the effort you have shown in supporting me through every single aspect of my research. Ian and Daryl, you have both been mentors and role models for me both professionally and personally and shown me how to act with integrity, patience and compassion.

I would like to thank the Njajma Rangers, Alfred Nayinggul, Kenneth Mangiru, Anita Nayinggul, Katie Nayinggul, Manbiyarra (Grant) Nayinggul, Tex Badari, Sebastian Nagurrgurrba, Hilton Garnarradj, Jacob (Junior) Nayinggul, Lawrence Nayinggul, James Dempsey, Ursula Badari, Timothy Djumburri, Thomas Falck, Daniel McLoney, and Shay Wrigglesworth who have all provided invaluable assistance in carrying out this research.

I would like to thank the Mimal Rangers and Elders, Jack Nawilil, Robert Redford, Abraham Weson for guiding me on through your country and providing invaluable assistance. I would also like to thank Peter Cooke for your support, hospitality and guidance throughout my research.

I have been lucky to work with a wide variety of incredible researchers and professionals have contributed to this research in countless ways, providing expert guidance and support. Thank you to Chantal Wight for your support, expertise and encouragement. Thank you to Mark Willis and Tristen Jones for your guidance both in the field and on the page. You have both provided me with expertise and insights that have contributed greatly to my research and my abilities as a researcher.

I would like to thank James Keal firstly, for always providing a sounding board for every idea that crosses my mind, but most importantly for the generosity of lending your expertise to see some of those ideas into fruition. The outcomes of this research would not have been possible without you and your incredible knowledge, skill, and enthusiasm.

I would like to thank Prakash Saraswati for always being there to find a solution to every problem that has me stuck. Throughout my entire thesis you have been my first port of call when a problem has come up and there has never once been a problem for which you can’t find a solution.

I would like to thank Mike Owen and Karen Dempsey for providing me a home away from home. Your support, generosity, and kindness in welcoming me to your home time and time again throughout my PhD research has been invaluable and making every trip north one that is full of great food, company, and encouragement.

I would like to thank my mother Julie Mitchel and to thank Ian Hendy-Pooley. You have both helped me more than I can express throughout my research and your support has been critical to the thesis I have been able to produce. I can’t thank you enough for making sure I can achieve my goals and that my work has been as good as it can be.

I would like to thank my friends and family who have been patient while I have worked on my PhD. Your patience support and encouragement over these years is greatly appreciated.

I would like to thank my Grandmother Valerie Mitchell, your support and encouragement throughout my life has given me the confidence and security to undertake anything I have wanted to achieve.

I would like to thank Shannon Barton, Josh Smith and my karate family for lending me their strength and helping me find mine.

To my nephew Teddy, thank you for always having a hug ready for me after a long day of writing, and brightening my day when I needed it the most.

I want to thank my incredible partner, Georgia Tuckwell. Georgia, you support me everyday to be the best person I can be. You have been my advocate (‘hype man’), my sounding board, my co-author, and every day you have helped me to achieve more than I ever knew I could. Like me, this thesis would not be what it is without you.

I would like to acknowledge the contribution to this research made through the Flinders University Research Scholarship which has provided fee offsets, stipends and research allowances that have made the work presented in this thesis possible.

LIST OF PUBLICATIONS DURING CANDIDATURE

Tuckwell, G, A., J. A. Keal, C. C. Gupta, S. A. Ferguson, **J. D. Kowlessar**, G. E. Vincent 2022 A Deep Learning Approach to Classify Sitting and Sleep History from Raw Accelerometry Data during Simulated Driving. *Sensors* 22(11):6598. https://doi.org/10.3390/s22176598

Kowlessar, J., Moffat, I., Wesley, D., Jones, T., Aubert, M., Willis, M., and the Njanjma Aboriginal Corporation 2022 Applications of 3D Modelling of Rock Art Sites Using Ground-Based Photogrammetry: A Case Study from the Greater Red Lily Lagoon Area, Western Arnhem Land, Northern Australia. In Ch'ng, E., Chapman, H., Gaffney, V., and Wilson, A. (Eds) *Visual Heritage: Digital Approaches in Heritage Science*. Springer. https://doi.org/10.1007/978-3-030-77028-0_6

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CHAPTER ONE

Chapter 1: Introduction to the Thesis

1.1 Introduction – Thesis Overview

The inscription of images onto natural rock surfaces is a globally occurring, incredibly varied and detailed artistic practice that has been occurring for at least 45,000 years. Referred to collectively, and for the purposes of this thesis, as 'rock art', these cultural markings take varied forms utilising carved and painted techniques (Whitley 2016: 23–24). From an archaeological perspective these artefactual images provide unique insights into rich cultural, spiritual and personal perspectives of past peoples that are not otherwise accessible through other aspects of the archaeological record. More widely, these artefacts are of significant interest and value for cross-discipline academics, cultural heritage tourism, and most importantly, for the Indigenous people to whom these cultural materials and artistic traditions belong, comprising an integral and ongoing part of their inherited cultural heritage. Each of these parties have different recording and management requirements informed by the nature of their engagement with the inscriptions.

Rock art is connected to landscape by the surfaces upon which it is placed. This relationship is influenced by deterministic factors such as the suitability of surfaces available for inscription, as well as the cultural factors that affect the choices of which surfaces to use and why (Schaafsma 1985: 261–263). This extends the challenge of recording and ultimately understanding rock art beyond the images themselves and into their spatial context. This spatial context can be on a local scale, such as understanding the arrangement and overlays of images on a panel, as well as on a landscape scale, which focuses on understanding the site selection strategies of rock art inscriptions. Such inquiries allow the knowledge to be gained from rock art research to extend to aspects of cultural engagement with local spatiality articulating with the extended environment across time. This speaks to the complexity of the task of recording, analysing and managing rock art as cultural heritage, which has given rise to a wide variety of theoretical and technical approaches. Added to this is the sense of urgency to record vulnerable sites driven by the encroachment of human and natural forces, such as mining and climate change, which threaten to destroy, alter and erase the archaeological record.

Recent digital approaches have revolutionised many aspects of archaeological research, presenting new means to collect, analyse and visualise data, allowing new ways of generating highly detailed three-dimensional data sets which have the capacity to hold spatial information with unprecedented clarity. While modern digital methods have provided new possibilities for all archaeological endeavours, visualisation is the central means by which rock art was intended to be engaged, making these approaches especially advantageous. Critically, the digital era of archaeology has recently brought about an entirely new paradigm of analysis with the advent of computer vision and machine learning. These new approaches allow the concept of visualisation to occur within digital analysis and allow this data to be engaged with by machine learning approaches. This is not simply a geometric engagement, but instead a true capability of ‘understanding’ and quantifying the concepts of visual ‘style’ in a profound and insightful way that is entirely new. This thesis demonstrates how these digital data sets can be deployed to allow exciting new ways to visualise and interact with archaeological data, particularly demonstrated here in the field of Indigenous rock art.

Digital approaches have also extended the ways in which landscape analysis can be conducted to provide precise contextualisation to rock art (Wheatley 1995; Wheatley and Gillings 2000). The exact spatial situation of rock art plays a role in the experiential engagement of the creator and subsequently the viewer and therefore may be a crucial component of its encoded meaning. A viewer is influenced by their sensory involvement at the given location in which they view the art, as well as by the journey they made to get there, which contributes to their overall experience of this art (Brady and Bradley 2014; Domingo et al. 2020; Taçon 1999). Similarly, the artists’ intentions when inscribing the art are impacted by all these factors, intentionally or otherwise (Higuchi 1988; Rouse 2018; Tilley 1994, 2008, 2010). Digital approaches have allowed the capture of a representation of the local space around rock art with incredible detail providing critical spatial contextualisation. Furthermore, modern digital landscape approaches allow the mapping and representation of the larger regional situation of rock art sites with high visual fidelity (Wheatley 1995; Wheatley and Gillings 2000).

However, the task of capturing landscape information is more complex than simply making a record of the contemporary landscape, as this does not necessarily describe the situation in which the art was inscribed and therefore intended to be viewed. Understanding ‘where’ rock art is situated is often a complex task that occurs in a theoretical space between objective and subjective archaeological approaches and centres on experiential engagement. Therefore, experiencing the archaeological models and data in the most engaging and realistic way is an advantage and specific goal of modern digital approaches, extending the landscape reconstruction task to the realm of palaeogeographic modelling and reconstruction. In this way enabling an enhanced comprehension of the temporal context relevant to the inscription event. Geophysical and geomatic methods provide a non-invasive opportunity to reconstruct the palaeogeography of rock art landscapes and so provide a temporally appropriate context. The results of these investigations can serve as inputs to other digital methods to facilitate immersive site investigation or visualisation.

As rock art research needs to be particularly receptive to the complexity of the environmental context and the nuance of the inscriptions, this thesis demonstrates new ways of recording each of these components, including new analytical approaches, which provide significant insights into the settlement strategies and environmental history of the specific target region. Additionally, by addressing the particular requirements for the use and development of new digital approaches to the complex tasks of rock art recording, management, and analysis, this thesis develops and demonstrates workflows which allow the initial rock art and landscape records ascertained to be repeatedly used for a variety of analyses. These include the investigation of style, structure, landscape context and environmental setting, while providing unique insights into each of these areas. For the purposes of this thesis, an area in Arnhem Land, northern Australia is selected for study. As an area rich in Indigenous rock art sites, it presents a perfect study area for this thesis to develop new rock art recording, management and analysis approaches. Figure 1.1 shows Arnhem Land along with other regional landmarks.

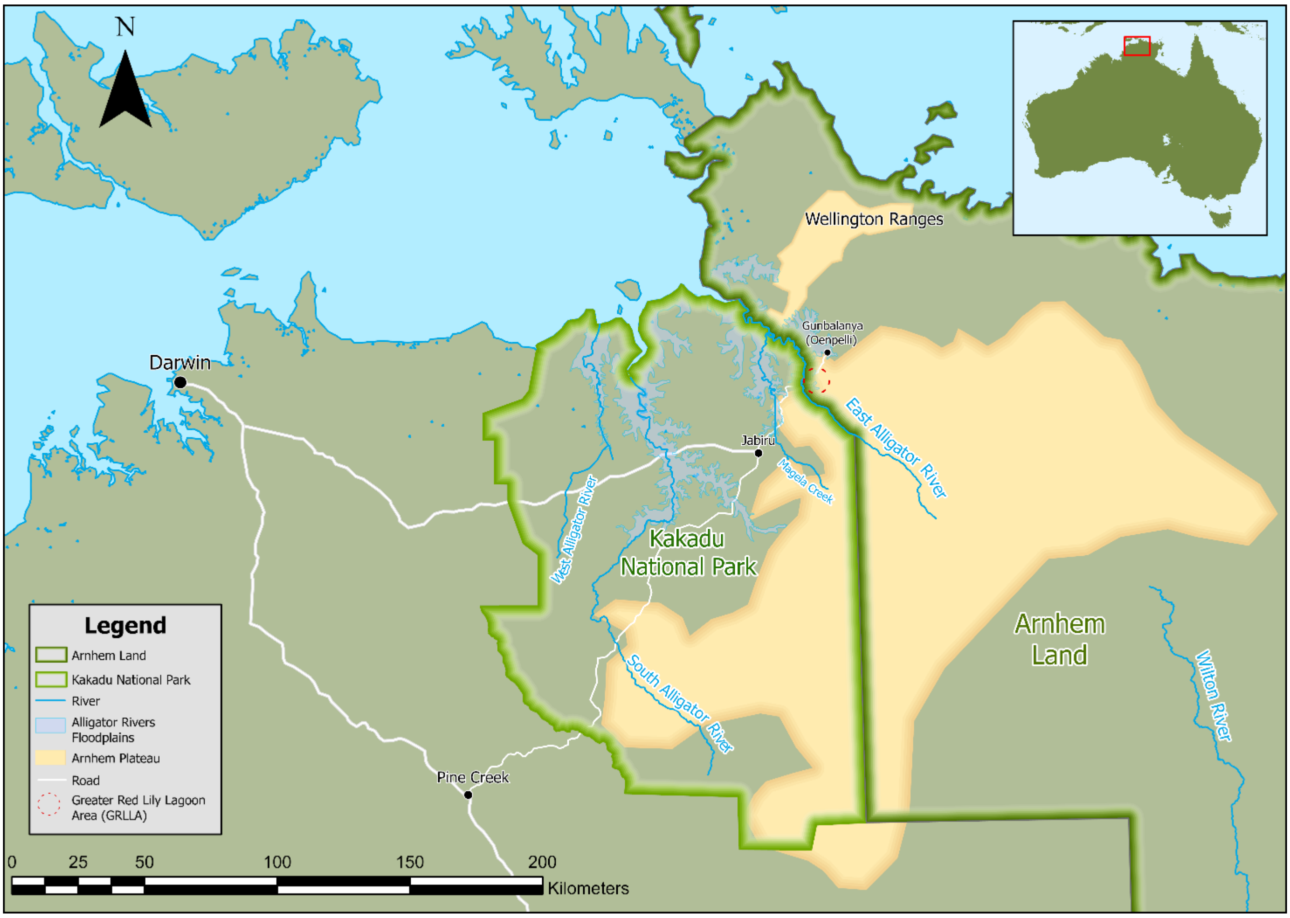


Figure 1.1 Arnhem Land, Alligator Rivers, and Kakadu National Park

Arnhem Land is a province of exceptional national and global significance with a vast assemblage of highly diverse rock art which has a long sequence of inscriptions. West Arnhem Land is the oldest known region to be inhabited by people in Australia, having been occupied by at least 65,000 years ago (Clarkson et al. 2017). During this extensive human history, rock art is known to have been created for at least 28,000 years (David et al. 2013a) but is likely to have been practiced for much longer (Clarkson et al. 2015; Jones 2017; Jones et al. 2017b). This deep history of human occupation is complemented by a vibrant contemporary art practice. Human occupation overlaps the dramatic climate and environmental changes associated with the transition from the last glacial maximum (LGM) through to the modern climate conditions. This phase has been demonstrated to have been associated with ~120 meters of sea level rise, causing profound changes to coastlines and water courses throughout northern Australia (Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1985). Rock art in this region provides a unique record of environmental engagement, social structures and occupation strategies through these significant climatic and palaeogeographic changes (Chaloupka 1993).

Within north-western Arnhem Land is a rock art province surrounding the culturally significant Red Lily Lagoon. Red Lily Lagoon and the Greater Red Lily Lagoon Area (GRLLA) are situated on the floodplains of the East Alligator River where the northern coastal plains of western Arnhem Land meet the sandstone escarpment of the Arnhem Land Plateau. This landscape has undergone dramatic environmental changes associated with the LGM, having transformed over time from a dry arid inland area to a coastal estuarine mangrove dominated swamp, then finally to the contemporary freshwater floodplains and wetlands of the late Holocene. These environmental changes are reflected in the subjects depicted in the rock art record of the region (Chaloupka 1993).

However, the relationship between rock art and place extends beyond the images and styles being depicted to include the landscape context of the art itself. It is this extended relationship between human creativity, material culture, spatiality and temporality within the broader environmental landscape that this thesis addresses, via the introduction of novel digital technological approaches and analyses. This provides a new means to discover, investigate, discuss, and disseminate the multiple relationships inherent within the existence of Indigenous rock art. Importantly, this work also enables the immediate 3D recording of vulnerable sites whilst providing a digital platform for access to otherwise inaccessible locations for traditional owners, thereby creating an alternative avenue of preservation and access to their own cultural heritage.

1.2 Research Questions

The major goal of this research is to develop digital approaches to aid in the field recording, stylistic analysis, landscape reconstruction, visualisation and dissemination practices applied to traditional Indigenous cultural rock markings. This will facilitate new understandings of past relationships with place and environment, speak to present day cultural heritage representations, and provide a technological bridge between historical cultural artefacts and future research requirements. Towards this end, the major research question of this thesis asks:

> How can emerging digital technologies be utilised to provide new insights into Indigenous cultural rock markings while serving the values of Traditional Owners, meeting the needs of cultural heritage management, and promulgating effective communication of archaeological models of the past?

To support this enquiry several ancillary questions are also posed which regard both the methodological framework as well as the settlement factors that can be observed through this landscape analysis.

> How can rock art be digitally recorded in a detailed and multivocal way which can serve as a record as well as a means of engagement and analysis with the site?
>
> What patterns of changes have occurred within rock art styles in Arnhem Land and how can we quantify these changes in a sensitive and continuous way?
>
> In what ways has the landscape changed over the history of rock art inscription in the Greater Red Lily Lagoon Area?
>
> How does the style and nature of Indigenous rock art inscriptions relate to their landscape context in Arnhem Land?
>
> What are the traditional land usage factors influencing site placement of Indigenous rock art sites in the Greater Red Lily Lagoon Area?
>
> How can we represent and engage with archaeological models of the past in a way that communicates the human experiences that are represented by these models?
>
> How does the holistic three-dimensional digital landscape analysis approach provide new insights into Indigenous cultural rock markings, customary practices, and traditional land use?

1.3 Research Aims and Expected Outcomes

To address the thesis questions this research aims to:

> Develop a methodological framework for the recording of rock art sites and their landscape contexts that addresses the cultural heritage management needs and archaeological analysis requirements of modern rock art research approaches.

Develop a digital approach to the objective quantification of rock art styles, which can organise a motif assemblage in a sensitive stylistic continuum.

Model the paleogeographic changes that have occurred over the history of human occupation of the Greater Red Lily Lagoon Area in a detailed way which enables the connection of the larger regional environmental changes to local rock art sites.

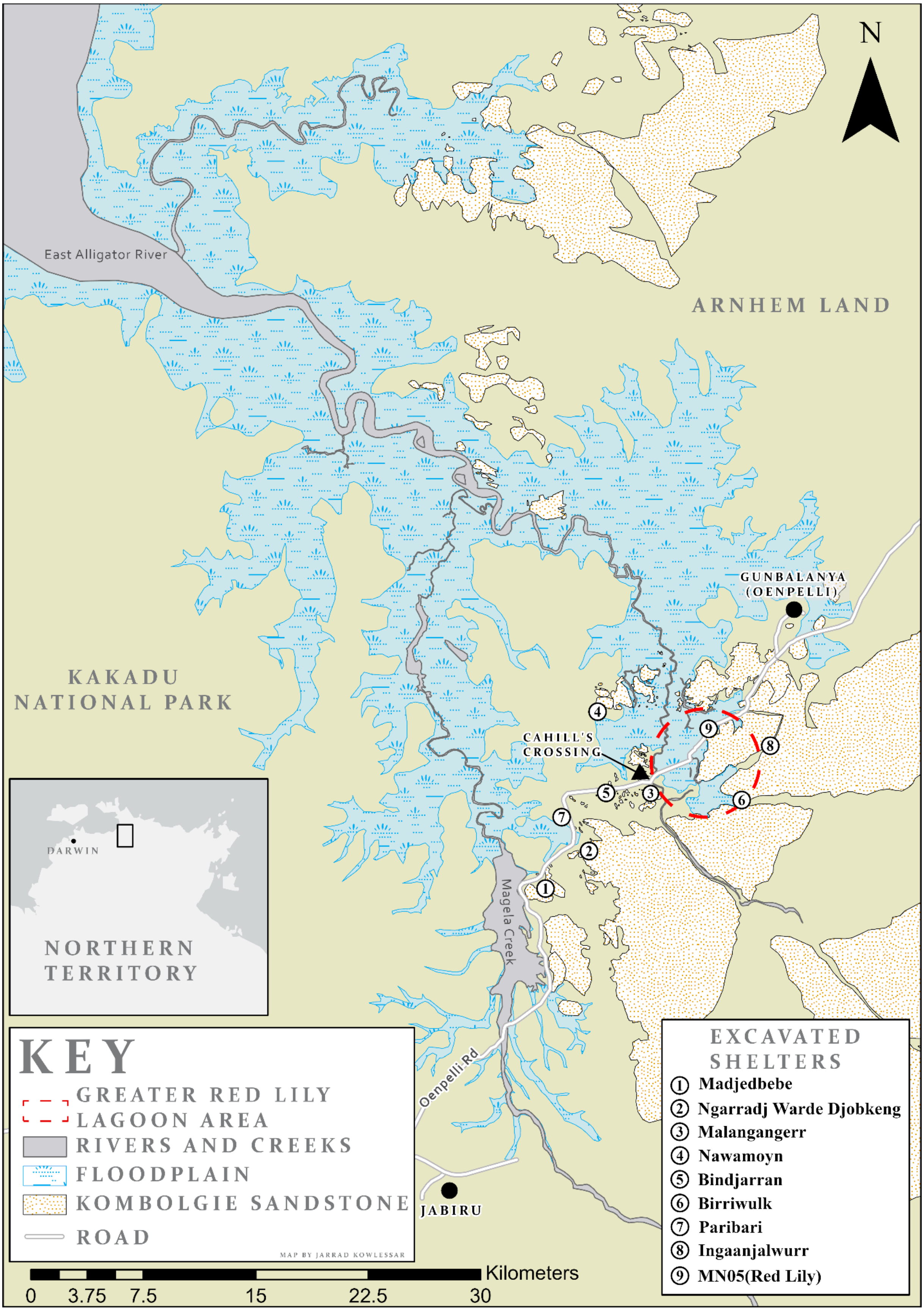
Investigate the spatial patterns within the placement of known rock art sites, with regard to the paleogeographies that were contemporary to their inscription, to better understand site placement strategies over time.

Develop a digital landscape analysis approach which allows visualisation and engagement with archaeological models of past environments to occur in an immersive way to best communicate the human experience.

1.4 Introducing the Research Area: Greater Red Lily Lagoon Area Background

The GRLLA is situated on Kunwinjku country within the Manilakarr clan estate, centred on the culturally significant Red Lily Lagoon, which is located 4 kilometres northeast of Cahill's Crossing directly adjacent to the Arnhem Highway as it leads to the nearby township of Gunbalanya. Red Lily Lagoon lies in the floodplains of the East Alligator River, which directly interfaces with the extensive Arnhem Land Plateau, an elevation region of 23,060 km² (Department of Agriculture Water and the Environment 2022) in the central of Arnhem Land. The East Alligator River catchment extends into the Arnhem Land Plateau where its headwaters begin, before leaving the sandstone reaches of the Arnhem Plateau and entering the valley plains, which extend from just south of Cahill's Crossing all the way to the ocean at Van Diemen's Gulf (Saynor and Erskine 2013). This situates the GRLLA on a section of the East Alligator River where the river transitions between the Arnhem Land Plateau and the low-lying floodplains. The Paleoproterozoic aged Kombolgie Formation dominates outcrops in the Arnhem Land Plateau, which contains the extensive sandstone escarpments, chasms and valleys that form the major canvas for cultural rock art inscriptions in the region.

The contemporary climate of this area in northern Australia is tropical with a seasonal wet/dry monsoon cycle. In the Arnhem Land region, the wet season typically spans from December to March but may extend some months either side. Cyclonic activity, high humidity and rainfall dominate the wet season whereas the dry season is characterised by dry conditions with moderate, stable temperatures from May to October (Reeves et al. 2013a; Samuel et al. 2021; Van der Kaars and De Deckker 2002; Wallis 2001). The wet-dry seasonality creates significantly different environmental conditions around the GRLLA, as the East Alligator River inundates the floodplains during the wet season (Woodroffe 1988). The climatic and environmental history of this region is further explored in Chapter four. Figure 1.2 shows the location of the GRLLA and surrounding geomorphology.



ESRI, GARMIN, FAO, NOAA, USGS

Figure 1.2 Map of the Greater Red Lily Lagoon Study Area showing the regional geomorphology and Excavated shelters.

1.4.1 Excavations and occupational Chronology

The Greater Red Lily Lagoon Area and the broader region have been subject to extensive archaeological excavation since 1981. The excavated rock shelters in this region are: Madjedbebe (also known as Malakununja II), Ngarradj Warde Djobkeng, Malangangerr, Nawamoyn, Bindjarran, Birriwulk, Paribari, and Ingaanjalwurr. An occupational chronology of the GRLLA can be inferred through the directly dated material excavated from rock shelter sites within the GRLLA or directly adjacent. Occupation at Madjedbebe has been dated to 61,000 (± 10,000 BP), which is the earliest known occupation in this region and indeed Australia (Clarkson et al. 2017). Figure 1.2 shows the locations of these excavated shelters. These excavations are discussed further in Chapters 4 and 5. This occupational history demonstrates an extraordinarily long period of human activity in this region which overlaps the significant climate events of Marine Isotope Stages (MIS) 3, (MIS) 2 which includes the significant LGM, and (MIS) 1.

1.4.2 Environmental History

Major climate changes driven by glacio-eustatic sea level fluctuations have occurred during the span of human occupation in the Greater Red Lily Lagoon Area with the sea level lower than present day for the entirety of the known period of human occupation until 6 ka when modern sea levels were reached. The lowest sea levels over this time were at least 120 meters below current levels at the Last Glacial Maxima (LGM) (~22 ka) (Allen and Barton 1989; Larcombe et al. 1995). Figure 1.3 shows the terrestrial area of the continent during the LGM at 22 ka. The Arafura shelf was exposed during this time and the contemporary mainland areas of Australia were connected to New Guinea. During this time the GRLLA region was approximately 300km from the coast, as compared to 50km in the modern day (See Figure 1.3). These changes to sea level and the major exposure of land surface had a significant impact on the climate of the GRLLA (Reeves et al. 2013a; Reeves et al. 2013b; Wasson 1992).

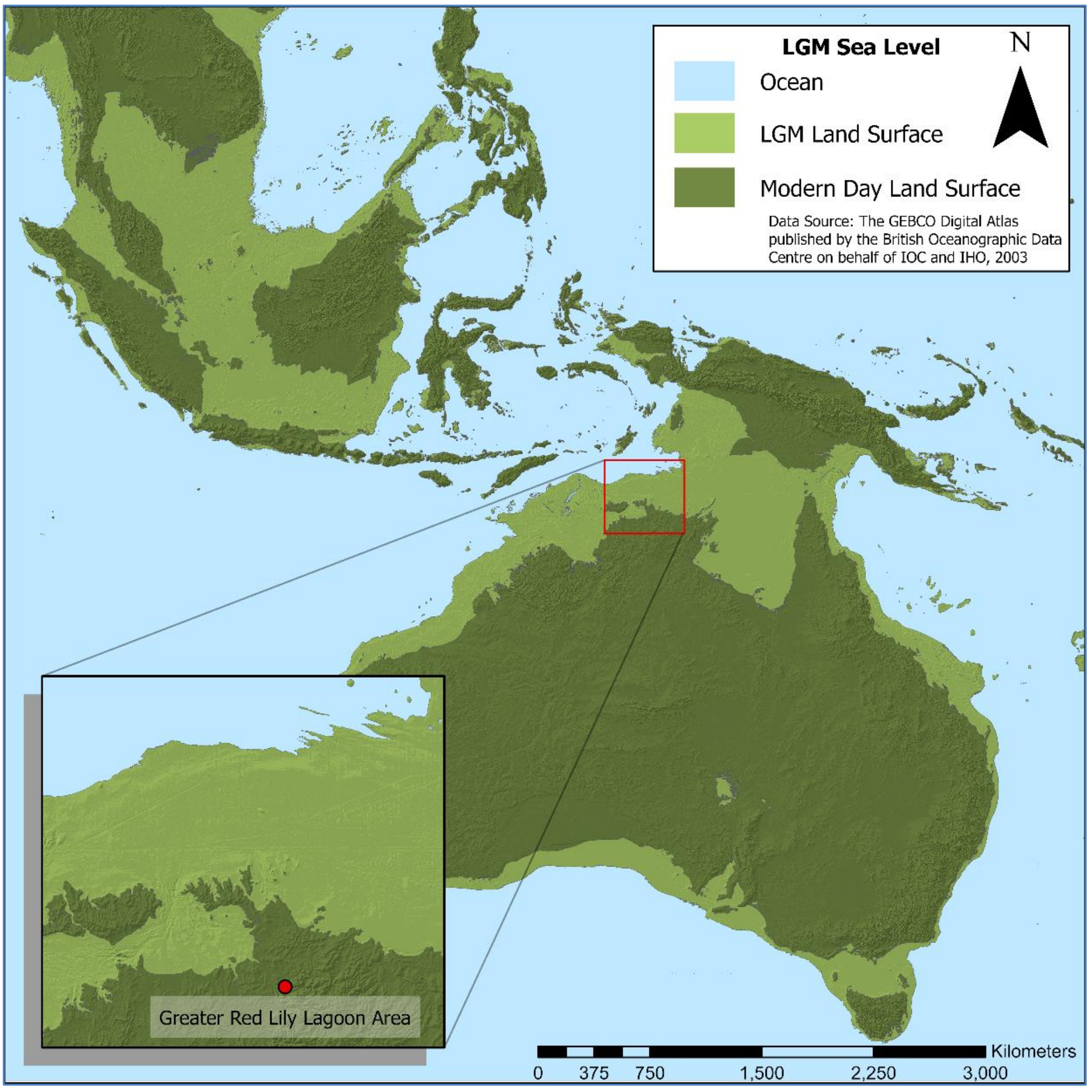


Figure 1.3 Deglacial sea level change folowing the Last Glacial Maximum

During the LGM a cooler and drier climate was present in northern Australia with possibly less than half the precipitation levels of today (Allen and Barton 1989: 7). Following the LGM, as temperatures warmed but sea levels remained lower than the Arafura shelf and Gulf of Carpentaria, there was a period of aridity. During this time the GRLLA has been characterised as having low open woodland environments, with vegetation similar to the semi-arid zones found in the modern-day Tennant Creek (which is located approximately 470 km inland from the coast and 800km south of the GRLLA) (Allen and Barton 1989: 7–10).

Between 13 ka and 10 ka sea level rise flooded the Sahul, and Arafura shelves. This flooding, along with the increased temperatures and warmer ocean currents, eventually activated the seasonal monsoon climate that is dominant today (Reeves et al. 2013a; 2013b). Eventually marine transgression reached the Alligator rivers and led to the flooding of the low-lying river valleys. With the extensive flooding of low-lying river valleys, the establishment of vast mangal forests (forests of a variety of mangrove species) filling these flooded valleys occurred (Woodroffe 1988; Woodroffe 1993). The extent of these mangroves has been well demonstrated across the South Alligator River and Magela creek floodplains (Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985), but their extent across the East Alligator River floodplains, especially in their landward extents remains speculative.

Sea levels stabilised at the modern-day level around 6 ka and freshwater carried by the seasonal monsoons became a major influence on the estuarine environments (Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985). The increased fluvial activity carried extensive sediment loads from the sandstone of the Arnhem Plateau to the mangrove dominated lowlands. Eventually this sedimentation caused significant coastal progradation transforming the lowlands into the freshwater floodplains of the Alligator rivers that are present today (Woodroffe 1988; Woodroffe 1993). This dramatic environmental history is further explored in chapter four.

1.4.3 Arnhem Land Rock Art

The paintings of Arnhem Land represent one of the world’s greatest collections of rock art. The rock art of Arnhem Land is extensive and varied, which follows the deep history of human activity in this region. The rock art of this region has been given a minimum age of 28 ka, however the maximum age of artistic practice in this region is likely to span back much further (David et al. 2013a). With a minimum human occupation date of over 60ka, the artistic practices in this region provide insights into significant narratives of social, spiritual and environmental occurrences (Clarkson et al. 2017). The artistic styles that are distinct to Arnhem Land occur widely from its western borders and into the adjacent Kakadu national park and all the way to its eastern coast in the Gulf of Carpentaria. The most recent artistic styles of this region are still practiced and evolving in the modern day with the inscription of new rock art paintings as well as a thriving culture of bark paintings as well as contemporary mediums (Goldhahn et al. 2021; McLean 2006; Taylor 1996).

The analysis of rock art in Arnhem Land has typically been conducted through a process of typological classification. Classification is useful for three main purposes: 1.) to understand the chronology of artistic practices in the region, 2.) to understand the regional differences between artistic practices and 3.) to understand the cultural associations of different artistic practices. Artistic practices or ‘style’ describes a particular way of producing art. Following these major purposes for rock art classification, style can be defined as: the variation in material culture over time and space which occurs when human activity is conducted in a particular way and in the context of alternative ways (Clegg 1987; Hegmon 1992).

This definition of style distinguishes one way of conducting activity from other alternative ways; a phenomenon which has been argued to arise from deeper functions of culture as well as personal and group identity (Gell 1998; Smith 1994). Style has been argued to have the primary function of information exchange, communicating something from the creator to an audience (Wobst 1977). This makes style, especially artistic style, a means of non-verbal communication or perhaps best described as a visual language (Wiessner 1990). As a visual language, a correct understanding or reading of the encoded information comes from a knowledge of the repeated patterns and representations that a given style uses to encode specific information (Wobst 1977: 322). These repeated patterns allow the efficient exchange of information within culturally fluent groups. This definition of style is sensitive to both space and time.

However, cultural changes over time can occur even within the same space and cultural boundaries influence the distribution and mixing of styles over space. Changes to the visual language might be expected to be gradual over time in the case of an uninterrupted isolated culture or express rapid or punctuated changes when influenced from an external cultural interaction (Lewis 1988: 101-102). Cultures that are connected may share some stylistic elements whereas those that are disconnected may appear distinctly. In this way, style may not act as a key to understanding the specific nature of the encoded information (which may be impossible from a culturally etic perspective), but instead may reveal the patterns and distributions of different past groups of people over time and space (Gell 1998; Lewis 1988; Smith 1994). On this basis, identifying the full range of distinct rock art styles and understanding their similarities has been a major focus of research in Arnhem Land.

An early stylistic classification scheme was developed by Brandl (1973) who organised the rock art of Arnhem Land into two chronological phases themed around two distinct cultural associations and ordered by the sequence of overlapping images (superimposition). These phases were Mimi art followed later by X-ray art (though there were additional categories within each). Mimi art describes red monochrome paintings commonly depicting humans in motion with refined, fine painted linework. These paintings have been named ‘Mimi’ art as Aboriginal people throughout Arnhem Land believe these images to have been painted by spiritual beings called ‘Mimi’ who live within the rock itself and can enter and exit at their will (Brandl 1973; Chaloupka 1993: 87; Gunn et al. 2018; Mountford 1956: 112). Brandl (1973) also considered technologies depicted within the art to further distinguish chronology in the older ‘Mimi’ phase with spear throwers being notably absent from the art that was considered to be the oldest. Additionally Brandl distinguished ‘older’ Mimi art from elements of posture and ceremonial regalia (Brandl 1973; Jones 2017). The X-ray art describes polychromatic artworks which typically depict subjects shown with internal organs visible. These were placed as the most recent phase in Brandl’s chronology and are an art style still practiced in the region today (Chaloupka 1993).

A second stylistic classification scheme and associated chronology of style was developed by George Chaloupka (1993) who built on this existing schema by further considering superimposition as well as considering the environmental context of the subjects depicted. In this way Chaloupka developed a four-phase chronology themed by the episodes of regional environmental changes which were: Pre-estuarine, Estuarine, Freshwater and Contact period. Chaloupka's scheme also included eleven styles (chronologically listed): Object imprints, Large Naturalistic Figures Complex, Dynamic Figures, Post Dynamic Figures, Simple Figures with Boomerangs, Northern Running Figures (named as Mountford figures in Chaloupka's scheme), Yam Figures, Early Estuarine Complex, Beeswax Designs, X-ray Complex and Casual Paintings.

Chaloupka's chronology has been subsequently re-evaluated and refined through additional fieldwork and the application of geochronological methods in Arnhem Land. There have been several amendments to the broad chronology that have been put forward based on continued research and observations of art throughout Arnhem Land (Chippindale and Taçon 1993, 1998; Taçon et al. 2020). These re-evaluations have placed importance on the 'principle of continuity' for further defining the chronological relationships between style (Chippindale and Taçon 1998). This principle argues that within the art record 'a particular feature will have been depicted over some continuous time-span rather than coming into the pictures, disappearing, and then recurring; therefore those styles with common features should fall adjacent to each other in the chronological sequence' (Chippindale and Taçon 1998: 102). Chippindale and Taçon (1993, 1998) used this principle to argue that the depictions of the boomerangs which occur in Dynamic Figure, Post-Dynamic Figure, Northern Running Figure, and Simple Figure styles must have a chronological continuity. Given the superimposition placement of the simple figures as the youngest of these styles it was argued that those Simple Figures that are depicted with boomerangs can be classified as a distinct and older group than the general Simple Figures style based on this feature (Chippindale and Taçon 1993, 1998). This re-evaluation, also found a number of superimpositions between Yam Figures and Simple Figures which place these two styles as chronological contemporaries. This was extended to make the argument that the two different styles relate to different cultural functions of the art with Simple Figures depicting subject matter of the human domain while Yam figures relate to the spiritual domain (Chippindale and Taçon 1998: 106).

Chaloupka's chronology and those subsequent revisions have been based principally on superimposition of interpreted styles. Distinct from this approach is a chronology put forward by Lewis (1988), which is based instead on a technological progression of the material culture depicted in the art. This chronology follows four phases: Boomerang Period, Hooked Stick Period, Broad Spear Thrower Period, and Long Spear Thrower Period. By ignoring superimposition and focusing on technological depictions this approach is highly limiting in how many motifs can be classified. Whilst Lewis' chronology provided an estimated time span of each phase, these time spans have been demonstrated to be problematic on their terminal ends with continued depictions of older technologies extending beyond these limits (Hayward 2017). Despite this, the model proposed by

Lewis (1988) does demonstrate a broad trend in technological depiction and highlights the increased stylistic variation which occurred following the appearance of the hooked stick technology (approximately 9 ka) within the art record.

Table 1.1 shows the Art styles of Arnhem Land in the approximate chronological position for each of the proposed chronologies alongside the environmental phases. These contrasting stylistic definitions and chronologies highlight the importance of revisiting the approach to stylistic analysis, especially from a digital perspective. Definitions of style are the principle means by which further research questions can be structured around rock art (Brady et al. 2019; Jones 2017). As such developments in this area are critical and should be seen as fundamental to progressing this field. The rock art styles of Arnhem Land are further explored in Chapter three and Chapter five.

Table 1.1 Rock Art styles of Arnhem Land by Environmental and Chronological Phases

Environment Phase	**Post glacial Phase** **~20 – ~13 ka**	**Sea level Rise Phase** **~13 – ~8 ka**	**Transgression Phase** **~8 – ~6.5 ka**	**Big Swamp Phase** **~6.8 – ~4.4 ka**	**Freshwater Phase** **~4.4 ka onwards**
Chaloupka's Chronology (Chaloupka 1993)	**Pre-Estuarine**	**Pre-Estuarine**	**Estuarine**	**Estuarine**	**Estuarine/Freshwater**
Revised Chronology (Chippindale and Taçon 1998)	**Old**	**Intermediate**	**Intermediate**	**Intermediate**	**New**
Technological Chronology (Lewis 1988)	**Boomerang**	**Boomerang–Hooked Stick**	**Hooked Stick**	**Broad Spear Thrower**	**Broad Spear Thrower – Long Spear Thrower**
Styles	Large Naturalistic fauna Hand Stencils (With 3 middle fingers together [3MF])	Dynamic Figures Post Dynamic Figures Northern Running Figures	Simple Figures w/Boomerangs Large Fauna Northern Running Figures	Simple Figures Yam Figures Large Human Large Fauna Early X-Ray	Complete Figure Complex Beeswax Figures X-Ray

1.5 Rock Art and Landscape Archaeology

Rock art is a widespread phenomenon that presents in spatial patterns throughout the landscape. These patterns clearly imply that terrestrial positioning plays a role in the process of rock art production and is therefore intrinsically connected to the meaning of this cultural practice (Bradley 1991, 1997; Bradley et al. 1994b, 1994a; Hartley and Vawser 1998; Ross and Davidson 2006; Schaafsma 1985: 261–263; Whitley 1998). The spatial distribution of rock art is fundamentally constrained by which locations offer the required physical conditions for rock art inscription. In this way the selection of such suitable locations, that is the geographical terrain, represents the canvas upon which this human activity occurs, so even at a preliminary level, understanding rock art positioning requires a detailed understanding of the environment contemporary with the inscription event.

However, the factors that influence site placement are clearly not exclusively determined by the environment, as not all suitable surfaces are painted, nor have the surfaces chosen been demonstrated to be randomly selected. Instead, the choices of suitable surface to paint extends to more complex cultural choices (Schaafsma 1985: 261–263). The cultural functions of rock art must therefore be considered as a major influence on the distribution of rock art sites across space. Cultural functions include, but are not limited to, spiritual, social, and territorial considerations, facilitating both the inscription, and the lasting presence of art in the landscape. It is for this reason that landscape approaches have been well suited for their application to rock art research and have a long theoretical history within the discipline of archaeology (David and Thomas 2016).

Importantly, landscape archaeology distinguishes the landscape as not one singular conceptual entity, but rather a palimpsest of overlapping conceptual landscapes which are all simultaneously navigated by humans therein. Landscape archaeology seeks to separate these conceptual landscapes and model them one at a time. In this way an archaeological landscape analysis may, for example, consider several facets of the social landscape at once, looking at the placements of social groups, territorial boundaries, and other social forces, as a holistic landscape. Furthermore, this social landscape may occur in the same location as an economic landscape which is characterised separately by different factors and boundaries, such as resource availability and seasonality, along with other different, separately characterizable landscapes, which could include Spirit-scapes, or physical landscapes (David and Thomas 2016; Forbes 2007; McNiven 2004; Westerdahl 1992).

Patterns within any one of these domains may be best detected and modelled using spatial analysis approaches which are typically conducted at a large regional scale where a collection of spatial information is analysed to determine broad geographic patterns. Given that the nature of archaeological data is only a small sample of past human activity, spatial analysis approaches conducted at a regional scale have the potential to maximise the information that can be gained from such data. Spatial analysis therefore, as an integral facet of rock art placements, can be related to other features within the landscape without a prior detailed cultural understanding of their intended function or purpose. Spatial analysis generally utilises a wide variety of data and analysis approaches to detect landscape patterns within rock art placements, including deterministic factors such as terrain and accessibility, proximity to landscape features such as water or other known resources (Acevedo et al. 2019; Bourdier 2013; Bourdier et al. 2017; Bradley 2002; Lenssen-Erz, 2004; Pastoors and Weniger 2011). Most recently, spatial analysis approaches have been revolutionised through the use of Geographic Information Systems (GIS) which serve as a digital platform to conduct such analysis, and currently new applications and technologies are emerging (Wienhold and Robinson 2019). The remainder of this section presents a brief discussion of the application of landscape analysis approaches to Indigenous cultural rock markings to date.

Traditionally, landscape analyses have commonly treated rock art as visual markers that are intended to be viewed at each location to provide further context and meaning to that place (Hartley and Vawser 1998). An example may be the use of rock art to mark the functionality of a location, for example, as related to food availability or storage, as territorial markers, or as culturally specific spiritual locations (Hartley and Vawser 1998). Spatial analysis is useful in this way to assess this proposed use of rock art as it can be demonstrated to have occurred in locations where its visibility is relevant to its proposed function, and its proximity to other landscape features can be demonstrated. The inscribing artist’s choice of location will fundamentally impact who sees the art, and in what context they see it. For example, an inscription used to mark a functional space (such as storage, area of important resource, territory boundary etc) is only effective for those people to whom visibility from known trails (paths, roads, rivers etc) is possible, thereby indicating this intended functionality (Hartley and Vawser 1998).

Conversely, art placed at locations of low visibility have been argued to be ‘hidden’ which may indicate that the intended audience is restricted to those with prior knowledge of its location. Such rock art locations can be interpreted as sacred places or hiding spots for sacred images (Domingo et al. 2020; Intxaurbe et al. 2020). Domingo et al. (2020) have challenged these interpretations of rock art visibility by providing examples of Australian Indigenous rock art which show rock art motifs with highly sensitive and secret meanings that are displayed in areas of high visibility as well as rock art panels which do not have secretive meanings associated or any other access restrictions yet are still located in areas of low visibility, thereby contradicting the assumptions required for both these interpretations of visibility. This ongoing debate around the facility of visibility to the intended functionality of rock art shows the difficulty of interpreting cultural function from spatial data alone.

Alternatively, a different approach to visibility analysis, concentrating on looking *in* at the rock arts sites, has been to consider the visibility of the landscape, or looking *out from* the locational situations of the rock art sites (Fairén 2010; Ruiz et al. 2021; Wheatley 1995; Wienhold and Robinson 2019). As this approach is focused on the location where rock art is inscribed and not the individual panel's exact visibility, this approach is distinct from the concept of intervisibility analysis and not simply reciprocal of the visibility of the rock art panel itself. This approach puts the human sense of place in focus and seeks to find ways to quantify the differences in such experience of place and the impact of the surrounding landscape. This sense of place is once again a combination of multiple landscape contexts combining in the mind of the human actor and as such can be analysed from several perspectives. At a most direct level, visibility approaches of this type have been used to describe social/territorial boundaries and strategic landscape control (Bradley 1991; Díaz-Andreu et al. 2017). These interpretations are made based on the physical spaces, paths and other such attributes that fall within the visibility of rock art sites when the entire landscape is considered (Fairén 2010; Ruiz et al. 2021; Wheatley 1995; Wienhold and Robinson 2019). Similarly, this approach may provide insights into the resource landscape by looking at what resources are present in those areas visible from rock art sites within a landscape (Fairén 2010; Ruiz et al. 2021; Wheatley 1995). This approach has also been used to understand more experiential human perspectives and help to quantify the sense of place that may be present at each rock art location.

The importance of establishing the human sense of place, and landscape impact for rock art sites is well demonstrated through the ethnographic accounts of cultural meanings associated with space. The impact of place as a critical component of Indigenous Australian creation stories, is argued to be in part due to the repeatable experience for all human beings who were to visit a specific place, especially true for distinct or unusual landscape features such as mountain ranges, gorges, caves etc., which invoke strong, and repeated human impressions (Taçon 1999). Indeed, rock art is often located at sites associated with creation stories where the power and significance of place has been culturally construed as being so potent that it is dangerous for people to go there without specific cultural practices and rituals performed (Domingo et al. 2020; Taçon 1999). Rock art sites may also be located at places of emotional impact and this network of places is associated with the mobility of people navigating this space (Brady and Bradley 2014; Domingo et al. 2020; Taçon 1999).

Visibility analysis approaches therefore, which seek to quantify aspects of the surrounding landscape's impact on the sense of place at rock art sites, have the difficulty of not just summarising what is visible, but of assessing the impact of this visibility (Díaz-Andreu et al. 2017; Rouse 2018; Wheatley and Gillings 2000). Some empirical measures have attempted to quantify some of these elements through spatial analysis by taking more 'egocentric' approaches, for example the concept of 'Higuchi viewsheds' as an empirical measure which attempts to quantify the visual 'aesthetic' of a place based on the visibility of the surrounding landscape (Higuchi 1988; Rouse 2018; Wheatley and

Gillings 2000). This approach considers the human eye and the distances from the observer to the subject which alter its impact on that observer (Higuchi 1988). For example, a forest at a close distance to a viewer will not just block a significant amount of visibility of other landscape elements but also has a much different impact and sense of scale than if it was in the far distance where individual trees may not even be distinguishable. This approach considers the ranges at which objects of different sizes can be clearly recognized by a human observer as well as the angle of observation, the texture of the objects and the interactions of light among other factors. This approach attempts to quantify the 'structure' of landscape by assessing these numerous factors as 'indices' and creating a value for each area/object and organising them in three distinct distance categories (short, middle and long range) (Díaz-Andreu et al. 2017; Higuchi 1988; Wheatley and Gillings 2000).

Soundscapes are another GIS based approach to quantifying the landscape impact but from the perspective of the sensory experience of sound. Soundscape approaches look at the physical structure of a location and model the acoustics of that place to determine the distance at which different types of sound might travel and in what ways this sound might be changed and distorted acoustically as it interacts with this physical surrounding (Díaz-Andreu et al. 2017; Díaz-Andreu and García Benito 2012). Research in this area is emerging but for the purposes of this thesis which does not explore sound specifically, is noted as a brief example of GIS based quantitative sensory spatial analysis

Therefore, while the area of spatial analysis which aims to quantify sensory, experiential, human perception is growing, there remains a considerable disconnect between the data/results produced by these approaches (images and maps) and the sensory reality of the landscape they describe as it would be experienced in person (Chapman and Gearey 2000; Kowlessar et al. 2019a). In this way, the results of spatial analysis approaches can only comment on the broader forces that influence past human behaviours and do not well model the conceptual landscape that individual actors navigate when they combine all these separate landscapes. Speaking to this, phenomenology is an exemplar of archaeological landscape approaches which aims to characterise these elements through direct experience of a landscape (Tilley 1994, 2008, 2010). Phenomenological approaches require that an archaeologist physically navigates the landscape they are studying in order to detect and interpret the specific sense of place that is invoked, and then apply this sense of place to interpretations of past human activities. In this way a sense of sight, sound, scent and other impacts of place are all achieved through experience. Furthermore, the specific task of navigation invokes not just a sense of a specific place within a landscape but also the journey to get there, the natural paths chosen and the feeling of this place in the context of such travel (Tilley 1994, 2008, 2010).

However, the difficulty of this approach lies in the subjectivity of the interpretation, with no clear way to scientifically validate or reliably reproduce results (Barrett and Ko 2009; Fleming 2006; Forbes 2007; Johnson 2012). The issue of subjectivity of phenomenological approaches in their purest form raises significant concerns for their applicability to archaeological landscapes outside of an archaeologist's own cultural setting (Johnson 2012). This extends beyond culture to other aspects of identity including gender, and personal physical mobility and sensory ability (Johnson 2012). All these unique aspects of personal identity will likely have profound influences on perceptions of place. Furthermore, the physical movement through a contemporary physical space is inherently imperceptive to landscape changes over time that may significantly change the landscape impacts of a place (Chapman and Gearey 2000).

Despite all these issues with the specific methodology of phenomenology, the theoretical perspective raises significant points about the way archaeology is conducted, especially in a landscape context (Johnson 2012). In review of phenomenology Johnson (2012:279) writes:

> We are all phenomenologists. Few archaeologists would now deny that it is necessary to consider issues of meaning and subjectivity to achieve full understanding of archaeological landscapes, and further that they would accept the starting point of the phenomenological tradition, namely, that understanding human experience is necessary but is not a commonsense undertaking.

This expands on Bender's (1998: 7) argument that even the most empirical approaches still require understanding and interpretation from an archaeologist and this is inherently a subjective element of all archaeological research. This important observation is a strong call towards integrating concepts of experiential engagement with archaeological data into all avenues of enquiry, in particular landscape approaches, where a sense of place is central to understanding the human activity of interest.

As outlined in this section, archaeological data can indeed provide empirical perspectives into the past configuration of rock art landscapes, but imagining the phenomenological reality of that place, especially within alternate temporalities, is an inherently cognitive approach. To address this, the use of digital methods in archaeology have been utilised to focus on the visualisation of archaeological data and to create models of past places, however, extending these visualisations now ventures into the space of 'Virtual Experience'.

1.6 Digital Archaeology and Virtual Experience

Visualisations of data (graphs, plots, maps etc.) to aid cognitive interpretation is intrinsic to many analysis. For spatial data these visualisations are often highly detailed and intuitive, based on all humans' inherent familiarity with navigating space. These representations of spatial archaeology data have been described as ‘Virtual Cultural Landscapes’, defined as ‘digital representation(s) of a past or hidden cultural space where people made decisions, such as where to live, hunt or collect resources’ (Monteleone et al. 2021: 383). This definition is further extended to include any ‘image, geographic information system, map or virtual environment that represents an area used by people’ (Monteleone et al. 2021: 383).

Indeed, it is contended that any interaction with a virtual cultural landscape carries with it phenomenological processing, knowingly or otherwise (Johnson 2012: 279). Digital Elevation Models (DEM) and geophysical data are excellent examples of landscapes and past landscapes that are often visualised in an intuitive 2D or even 3D way (Monteleone et al. 2021). These models can be used as a framework to unite other sources of data into a cultural virtual landscape. This presents a means by which not only can the data be ‘experienced’ but also a model of the past landscapes this data represents can be experienced too. These past landscapes, especially in the case of geophysical models, may no longer be engaged with in any other experiential way (Monteleone et al. 2021).

When we consider the function of rock art in this way, as an intentionally visual medium, the experience of this material culture, both in its creation and in consequent viewings, is therefore a critical component of its function because the significance of a given human artistic expression is imparted both through the artist’s intentions and a viewer’s impressions. The meaning encoded into rock art therefore may speak to a cultural means of communication that is deeply connected to the specific cultural background as well as to the personal identity of the artist. What has been inscribed, where it was inscribed, and when it was inscribed, are all critical components of this combined ‘meaning’. A second meaning occurs through the act of observation, carrying with it different cultural values and conceptual visual language. The human experience of all aspects of rock art is therefore a fundamental aspect of its function and the carrier of some of its unique properties (Chippindale and Nash 2004).

It follows then, that any visualisation of rock art should strive to consider the context of its creation and experience the location of its intended viewing as much as feasible. Viewing landscape art outside of this context is comparable to studying an incomplete or broken material artefact and is subject to similar limitations. In the case of substantial paleogeographic/environmental changes, as have been well demonstrated throughout the Holocene for the GRLLA, the intended experience of such a location must require environmental modelling and digital visualisation.

1.7 Thesis Organisation

Throughout this thesis, digital approaches are reviewed, designed and deployed towards achieving the overarching research aim, which is to develop new digital approaches to rock art recording and analysis. Towards this goal, the Greater Red Lily Lagoon Area, with its abundance of rock art and long history of human activity, provides an ideal setting from which to address the research. This thesis therefore also serves as a single body of research which concomitantly records and analyses the rock art and associated environmental history of this area, adding new information to the historical record while preserving existing data with innovative technological advances.

Structurally, the chapters are presented to highlight each aspect of the archaeological research design addressed, that is, background research, data collection and recording, stylistic analysis, geophysical modelling, landscape analysis, and 3D visualisation, all of which speak specifically to the research questions and aims listed in the introduction. Building on each other, while also quite capable of standing alone, the chapters culminate with a concluding discussion chapter tying the aims, outcomes and future applications of the introduced digital methodologies into a comprehensive investigation of the Greater Red Lily Lagoon Area for academic as well as Indigenous custodial uses.

Designed with the needs and requirements of both archaeological and Traditional Owners in mind then, this thesis contains five stand-alone chapters which each address a significant aspect of rock art research, as well as contributing to the collective record of the GRLLA. Chapters two through four present these standalone research papers which act as case studies within this thesis. Each of these chapters have been submitted to peer-reviewed academic publications, but together these papers form the larger body of research presented in this thesis. All research has been carried out with the authorisation and assistance of the Indigenous custodians, and will be theirs to access virtually, which is particularly helpful for dissemination with such areas of difficult accessibility.

Chapter one has introduced the thesis questions, aims, and research area, while providing brief background discussions regarding the locational landscape, previous rock art studies, technological perspectives, and archaeological methodologies.

Chapter two examines rock art recording methods for the purpose of analyses, as well as for support to the cultural heritage management of rock art sites. Responding to the challenges faced by Indigenous custodians and archaeologists in an Australian cultural heritage management setting, this chapter presents a new rock art recording methodology that has been designed to develop cost effective digital records of rock art sites that fit the wide variety of purposes that rock art recording serves. This methodology provides the primary rock art data collection used within this thesis, and also describes the field work conducted to collect this dataset, thereby achieving the first aim of this thesis, to develop a methodological framework to record rock art sites and landscapes that addresses both future cultural heritage management and analysis requirements.

Chapter three presents a novel machine learning approach to stylistic analysis of rock art. This chapter examines the challenges faced by traditional approaches to rock art stylistic analyses, before presenting an alternative which increases the sensitivity of stylistic analysis to detect and quantify subtle regional patterns as well as chronological changes in style over time. This chapter takes motif examples from the GRLLA and compares them with datasets collected in the Wilton River Region of East Arnhem Land, and to published images from across a wide variety of sites in Arnhem Land. The results presented in this chapter act as an important framework for enhanced understanding of stylistic changes within the GRLLA and Arnhem Land more broadly. In this chapter therefore, the second aim of this thesis is realised, and demonstrated by the development of an operational digital approach to the objective quantification of rock art styles that is able to organise a motif assemblage in a sensitive stylistic continuum.

Chapter four presents a detailed geomorphological analysis of the GRLLA using geophysical and geomatic survey methods. This chapter presents a detailed review of the environmental history of the region demonstrating significant climate driven landscape changes over the course of human rock art inscriptions within the region. This chapter reconstructs the palaeogeography of four major environmental phases of the GRLLA, spanning from the late Pleistocene to the modern day. This important landscape reconstruction acts as a critical framework for understanding the environments contemporary to rock art inscription and achieves the third aim of this thesis by using advanced geophysical technology to create a working model of the paleogeographic changes over time, connecting the local rock art site to the larger regional environment.

Chapter five presents a GIS based landscape analysis of rock art site placement within the GRLLA. This chapter builds on the stylistic and environmental chronologies developed in the previous chapters to connect individual rock art inscription sites to the palaeogeography that was contemporary to these inscription events. This chapter makes use of visibility analysis to help quantify key differences in landscape use between the major environmental and social phases of rock art production within the GRLLA. This work completes the fourth aim of this thesis by producing a paleographically derived spatial landscape analysis to comment on original placement strategies.

Chapter six unifies the outcomes of each of these chapters though a highly immersive virtual cultural landscape. This chapter presents a novel approach to virtual cultural landscape development through the use of the Unreal engine game development platform. This visualises photogrammetry models, geophysical and remotely sensed data and derived vegetation and geomorphology models into a single cohesive digital landscape, decorated with realistic 3D assets representing vegetation and other natural features. This approach is used to generate separate landscape visualisations for the key paleoenvironmental period of the landscape following the last glacial maximum. Novel ways of interacting with these virtual cultural landscapes are explored including virtual reality platforms as well as traditional 2D image rendering.

Chapter seven revisits the research aims and questions for the thesis and discusses the outcomes derived by the practical applications conducted in the work of the thesis in researching, field work, analyses and technical digital applications developed and deployed to address and answer these. This thesis concludes with a holistic discussion of the additions to the archaeological knowledge, both practical and theoretical, that these new approaches to digital landscape approaches to rock art explored, and any recommendations for future improvements.

CHAPTER TWO

Chapter 2: Applications of 3D Modelling of Rock Art Sites Using Ground-Based Photogrammetry: A Case Study from the Greater Red Lily Lagoon Area, Western Arnhem Land, Northern Australia

An earlier version of this chapter was published in *Visual Heritage: Digital Approaches in Heritage Science:* Kowlessar, J., I. Moffat, D. Wesley, T. Jones, M. Aubert, M.Willis, A. Nayinggul, and the Njanjma Aboriginal Corporation 2022 Applications of 3D Modelling of Rock Art Sites Using Ground-Based Photogrammetry: A Case Study from the Greater Red Lily Lagoon Area, Western Arnhem Land, Northern Australia. In Ch'ng, E., H. Chapman, V. Gaffney and A.S. Wilson (eds) *Visual Heritage: Digital Approaches in Heritage Science*, pp.93–114. Gewerbestrasse: Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-77028-0.

Approximate contribution of co-authors: Jarrad Kowlessar (65%), Ian Moffat (5%), Daryl Wesley (5%), Tristen Jones (5%), Maxime Aubert (5%), Mark Willis (5%), Alfred Nayinggul (5%), and the Njanjma Aboriginal Corporation (5%).

2.1 Abstract

The creation of high-resolution 3D models using structure from motion (SfM) photogrammetry is an emerging research tool in archaeology that allows the spatially accurate representation of rock art sites and landscapes. This methodology allows the creation of immersive representations of important cultural-heritage sites using widely available, inexpensive equipment and software which produce data that can be easily managed by the appropriate Indigenous custodians. In this study, ground-based photography was used to create high-resolution, georectified three-dimensional (3D) models of five rock art sites in the Greater Red Lily Lagoon Area (GRLLA) in western Arnhem Land, Northern Australia. Located directly between the East Alligator River and the Arnhem Plateau, on the Traditional Lands of the Australian Indigenous Manilakarr Clan, the rock art and cultural-heritage sites present in the GRLLA are of national heritage significance and are immediately adjacent to World Heritage-registered Kakadu National Park. This corpus of rock art is threatened by limited land management resources, tourism and visitor pressures, and land access issues. The creation of high-resolution 3D models of rock art using SfM photogrammetry provides a cost-effective approach to assist Indigenous cultural-heritage land managers to manage, record, and monitor rock art sites and enhance site access and visitor experiences.

2.2 Introduction

Red Lily Lagoon and the Greater Red Lily Lagoon Area (GRLLA) are situated on the edge of the northern coastal plains of western Arnhem Land, Australia (Figure 2.1). This environment is at the interface between the ‘stone country’, consisting of an elevated sandstone plateau incised by multiple gorges, and the floodplains surrounding the East Alligator River. This landscape is argued to have been continuously occupied by humans for over 60,000 years (e.g. Clarkson et al. 2017; Clarkson et al. 2015) and in that time has seen dramatic paleogeographic change driven by sea-level variation (Reeves et al. 2013a; Woodroffe 1988; Woodroffe 1993). During this extensive human occupation, inhabitants have left significant cultural markings in the form of painted and engraved rock art on the sandstone of this province (Chaloupka 1993; David et al. 2013a; 2013b). These sites present a unique Indigenous vision of society and environment (Gunn 2018) and have great cultural significance to the Traditional Owners of this landscape (Gunn 1992; Guse 2008; Jones and Wesley 2016; Wesley 2016). Unfortunately, these important sites are under an increasing threat from a diverse range of natural and anthropogenic taphonomic processes including weathering, road usage, site visitation, and wildfire damage (Carmichael et al. 2018; Guse 2008; Marshall 2020; Wesley 2016).

Rock art sites of the GRLLA present significant challenges for cultural-heritage management as well as archaeological research. The primary challenge is to develop a time- and cost-efficient methodology for making a detailed record of the complex natural and cultural structures of rock art sites, including both the individual rock art motifs and the site physiography. This record must be of sufficient resolution and clarity to facilitate ongoing site management and monitoring as well as providing a means of cataloguing and organising motifs. This challenge is made more difficult by significant limitations to site access caused by seasonal flooding and inaccessible terrain. This drives a need for a detailed site recording methodology that is highly time efficient and limits the use of heavy and difficult-to-transport equipment. A 3D approach to site recording and representation using ground-based photogrammetry allows these management outcomes to be achieved. The data produced by this methodology provide a means to view and experience the sites in a meaningful and immersive way from a remote location. Given the need for site conservation and the remote location of many rock art sites in the region, virtual site access is a valuable product for Traditional Owners, land managers, and researchers who can perform spatial queries and analyse directly on virtual representations. Despite the efficacy of these digital products for satisfying Indigenous and researcher needs, they may create significant challenges for the management, curation, and dissemination of this culturally sensitive virtual repository. This chapter presents a case study of digital recording of rock art sites in the GRLLA using structure from motion photogrammetry (SfM) and explores an approach to the accessibility and management of these digital records for purposes of virtual site access, site management, and future potential applications such as virtual tourism.

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 2.1 Greater Red Lily Lagoon Area rock art study area

2.2.1 Greater Red Lily Lagoon Area Rock Art

The GRLLA includes Red Lily, or Wulk in Erre language, Lagoon located adjacent to a dense concentration of cultural-heritage sites (known as Minjamirndaab) depicting thousands of rock art inscriptions, which are situated where the Arnhem Land escarpment meets the floodplain and wetlands. The geology of the area is predominantly sandstone, quartzite, and conglomerate bedrock, with igneous intrusions and extensive areas of lateritic formations from the Tertiary period (Christian et al. 1953; Needham 1984; Senior and Smart 1976; Sweet et al. 1999). The cultural-heritage site complex, Minjamirndaab, consists of 77 known rock art sites, including a number of dreaming (djang) rock art sites, in particular a site known as Urrmarning (Red Lily Dreaming) (Wesley et al. 2017).

The GRLLA first came to prominence for its rock art after the 1949 AngloAmerican Scientific Expedition to Arnhem Land (Mountford 1950, 1956, 1964, 1965, 1967, 1975). The area of sandstone escarpment adjacent to Wulk Lagoon was called Inagurdurwil by Mountford (1956) (although this is a name no longer recognised by Manilakarr Traditional Owners). Mountford (1956) was particularly attracted to the detailed hunting scenes and discussed in detail the significance of the rock art which included images of running figures and men hunting from the Inagurdurwil galleries (Jones et al. 2017a; 2017b). Mountford (1964: 12) referred to the rock art of western Arnhem Land as by far the most colourful known in Australia, with specific reference to the paintings at Minjamirndaab. McCarthy (1965) described X-ray and ‘spirit’ paintings from rock shelters in the GRLLA. McCarthy (1965) discussed *Mormo* and *Mimi* spirits along with the purpose of Indigenous religious and ceremonial aspects of the rock art and cultural knowledge held by Manilakarr Traditional Owners. Edwards (1974: 136) recognised the GRLLA (Minjamirndaab) as one of the most significant complexes of rock art in the region. Edwards (1974: 37–38) noted the numerous painted ‘scenes’ of ceremony, dancing figures, and didgeridoo players whilst stating that hunting and fighting scenes are a major feature of the precinct. Further research at GRLLA was undertaken by the well-known Czech physical anthropologist Jelinek (1986) who attempted to place the rock art from the area into a generalised study of greater western Arnhem Land rock art. Rock art from Red Lily Lagoon would feature as key examples in Chaloupka’s (1993) regional rock art stylistic chronology. Chaloupka (1984: 34–35) observed that the best examples of Northern Running Figures are found in these site complexes. Gunn (1992) undertook a detailed survey of GRLLA concentrating on recording rock art imagery from sacred sites including Urrmarning. This is the last known recording of Urrmarning before it was destroyed in 2006 from wildfires. The Red Lily Lagoon area has been shown to be an area of intensive rock art production during the late Holocene with a focus on depicting human figures and fish (Wesley et al. 2017). Rock art sites in this area have also contributed to significant advances in the understanding of Arnhem Land rock art chronologies (Jones et al. 2017a; 2017b). Radiocarbon age determinations for the Northern Running Figure rock art have produced a minimum age of 9400 cal. BP, suggesting a production range of over at least 3500 years (Jones et al. 2017b: 88).

An important consideration for understanding GRLLA rock art is to place it within the context of the occupation of Arnhem Land over the last 65,000 years (Clarkson et al. 2017; Jones 1985). Significant environmental variability occurred during this period resulting in substantial landscape alteration which all strongly influenced the geomorphological development and ecology of Arnhem Land (Wasson 1992; Woodroffe 1988). The combination of climate variation, sea-level rise, and palaeogeographic change throughout the period of human habitation provided the impetus for considerable disruption and change to occupation and land use and to the emergence of new rock art traditions and other technologies (Bourke et al. 2007; Faulkner 2009; Hiscock 1996, 1999; Jones 2017; Taçon and Brockwell 1995). Models of rock art chronology and Indigenous occupation closely mirror these environmental changes (Chaloupka 1993; Hiscock 1999). Occupation of the GRLLA has been investigated through excavations at three rock shelter sites: Birriwilk (Shine et al. 2013), Ingaanjalwurr (May et al. 2017; Shine et al. 2016), and Minjamirndaab (MN05) (Wesley et al. 2017). These three sites all show that the highest occupation density occurred in the last 1000 years associated with a focus by Indigenous people on the nearby freshwater environment of the East Alligator wetlands that emerged in the late Holocene (Shine et al. 2013, 2016; Wesley et al. 2017). The archaeological connections to the freshwater environment correspond with djang (dreaming) (Shine et al. 2013: 76) and associated cultural narratives (May et al. 2017: 62) and suggest that much of the rock art production is dated to the last 750 years at these sites. The cultural-heritage sites of the GRLLA and the rock art depictions therein provide a lens through which to explore the nature and magnitude of change in Indigenous communities that have occurred over millennia and, thus. are exceptionally significant for both the Indigenous Traditional Owners and archaeological research.

The destruction of the Urrmarning dreaming rock art site by wildfire in the aftermath of Cyclone Monica in 2006 prompted senior Traditional Owners to seek professional and academic support to ensure cultural-site safety through a local management approach. The Njanjma Aboriginal Corporation (NAC) and an Indigenous ranger program were established in response to concerns by Traditional Owners regarding the ongoing management and conservation of their country. By 2015, NAC had identified the conservation of rock art and other Indigenous cultural-heritage places as a major priority for Traditional Owners (Njanjma Rangers 2015). The rock art sites of the GRLLA are managed by the Njanjma Rangers who are tasked with locating, monitoring, and conserving rock art and Indigenous cultural heritage (Njanjma Rangers 2015). Detailed records of cultural-heritage places are required for conservation planning and management. Accurate and detailed records are important as a tool to allow Indigenous rangers to monitor conditions at the rock art sites. A wide variety of micro and macro threats to the rock art sites have been noted in a number of studies in the GRLLA (Guse 2008; Marshall 2020; Njanjma Rangers 2015; Wesley 2016). Primary risks to all sites include encroaching vegetation and weeds, insects (i.e. termites and mud-wasps), dust, weathering and erosion, mineral deposits and staining, fire, visitation, and changes to rock surfaces such as exfoliation and cracking (Guse 2008; Marshall 2020; Wesley 2016). These risks to the rock art of the GRLLA are not inconsequential and can result in the catastrophic loss of rock art as seen at Urrmarning (Wesley 2016). Furthermore, there is a tangible risk to rock art from climate change (Carmichael et al. 2018). Monitoring these impacts requires a constant and detailed record of rock art conditions.

2.2.2 Aims of a Digital Approach to Rock Art

Rock art recording (summarised by Domingo Sanz 2014) is primarily aimed at making as detailed a record of the site as possible to facilitate research, accessibility, and cultural-heritage management. This has historically been undertaken by drawing, photography, site plans, or surveying (Brady et al. 2019). This record can serve a multiplicity of functions, depending on the aim of the survey, but digital technologies now make it possible to record data of sufficient resolution to address all of these aims (Alexander et al. 2015; Chandler et al. 2007; El-Hakim et al. 2004; Meijer 2015). As a result, SfM photogrammetry is now becoming a widely applied tool in rock art research (Brophy 2018; Davis et al. 2017; González-Aguilera et al. 2009; Scopigno et al. 2011).

One important goal for the recording of rock art is to document changes to the site over time to quantify deterioration and to identify its key agents (Plets et al. 2012). For change detection, a geometric record of the site must be generated as well as a detailed visual record of every motif present. This has traditionally been undertaken for rock art with photography (Groom 2016) but SfM photogrammetry is much better suited to this task (Plets et al. 2012), and data of this resolution provide the opportunity for automated change detection (Abate 2019).

An additional goal of site recording is to facilitate remote interaction with rock art, principally using virtual reality techniques. This goal was designed to allow interaction for management purposes (i.e. Lee et al. 2019) as well as for providing access to community members with limited mobility. Similar approaches are used in a routine way for built heritage (e.g. Greenop and Landorf 2017) but have rarely been used for rock art studies(Alexander et al. 2015; Rogerio-Candelera 2015).

In addition to providing information for cultural-heritage management and community engagement, rock art recording aims to produce a data set detailed enough to allow analysis for archaeological research. This requires accurate scale information for the site and each motif depicted therein. This has traditionally been accomplished by including a scale bar within rock art photography, but this doesn’t allow accurate measurement of individual features when used in a single photograph. Additionally, the placement of the motifs within the geometry of the shelter and their relative positions to one another are critical to archaeological rock art analysis. This has traditionally been accomplished in rock art studies by drawing a baseline offset plan of the site or with a compass and tape. The placement of the site in its contextual landscape is also of critical importance so that its aspect, elevation, and relationship to other landscape features can be determined (Bradley 1991; Bradley et al. 1994b).

In addition to these considerations, the chosen method of recording would require low cost equipment as well as a rapid recording method (Westoby et al. 2012). This is important as this region has an abundance of rock art sites and access is severely limited by precipitous terrain, seasonal flooding, and pockets of thick forest. As a result, much rock art recording is undertaken using a helicopter to access the sites.

2.3 Methods

Structure from motion photogrammetry (SfM) (reviewed for archaeological applications by Sapirstein and Murray 2017) was chosen as the method of three-dimensional recording of the rock art sites. SfM generates spatial measurements from multiple digital images and ultimately can digitally reconstruct an entire area or a discrete subject in three dimensions. This method requires multiple digital images taken of the same subject from many different angles and camera positions. The SfM photogrammetry method reconstructs the camera locations by first detecting features present in multiple images and then computing the changes in the angle that account for the differences between images (Westoby et al. 2012). By reconstructing the camera position of each image, the distance between subject and camera can be calculated. This method has a two-phase workflow: data capture followed by data processing.

The SfM method has been employed numerous times in an archaeological context for Indigenous Australian rock art recording (Davis et al. 2017; Fritz et al. 2016; Jalandoni et al. 2018). In some cases where persistent site access is possible, the process of data capture has been approached iteratively. In these cases, issues with data capture that become apparent during post-processing can be easily resolved with a site revisit (Fritz et al. 2016). This approach is not applicable throughout the Njanjma management area because most sites are situated in difficult-to-reach terrain which severely limits the opportunity for revisit. Therefore, complete capture in one visit is a requirement. Iterative site visits are possible, however, on a longer time scale for the purposes of change detection.

For this case study, using SfM, data have been collected and modelled separately for comparison in 2015 and again in 2019. To achieve this, a detailed visual inspection of every surface of each recorded rock art site was conducted before SfM image capture to ensure the recorders complete capture of every motif and required site feature. To aid in the detection of faded pigments, the DStretch image enhancement software (Harmon 2009) was run on a portable Android tablet. DStretch provides a number of pre-set contrast ratios that can recolour digital images to accentuate a variety of faint pigment colours (Figure 2.2). A number of colour space enhancements are available through the DStretch software which accentuate different pigment colours. The LYE enhancement, for example, accentuates yellow colours which are often very difficult to observe even with close-up visual inspection on site. Whilst every surface will be recorded and DStretch can be performed in post-processing of the SfM constituent image set, the live surface inspection was also conducted to ensure that any visible pigments are located and imaged in appropriate detail and distance during the SfM image capture (Davis et al. 2017: 5). After conventional and DStretch images demonstrated the presence of rock art motifs, we proceeded to capture images suitable for constructing SfM models.

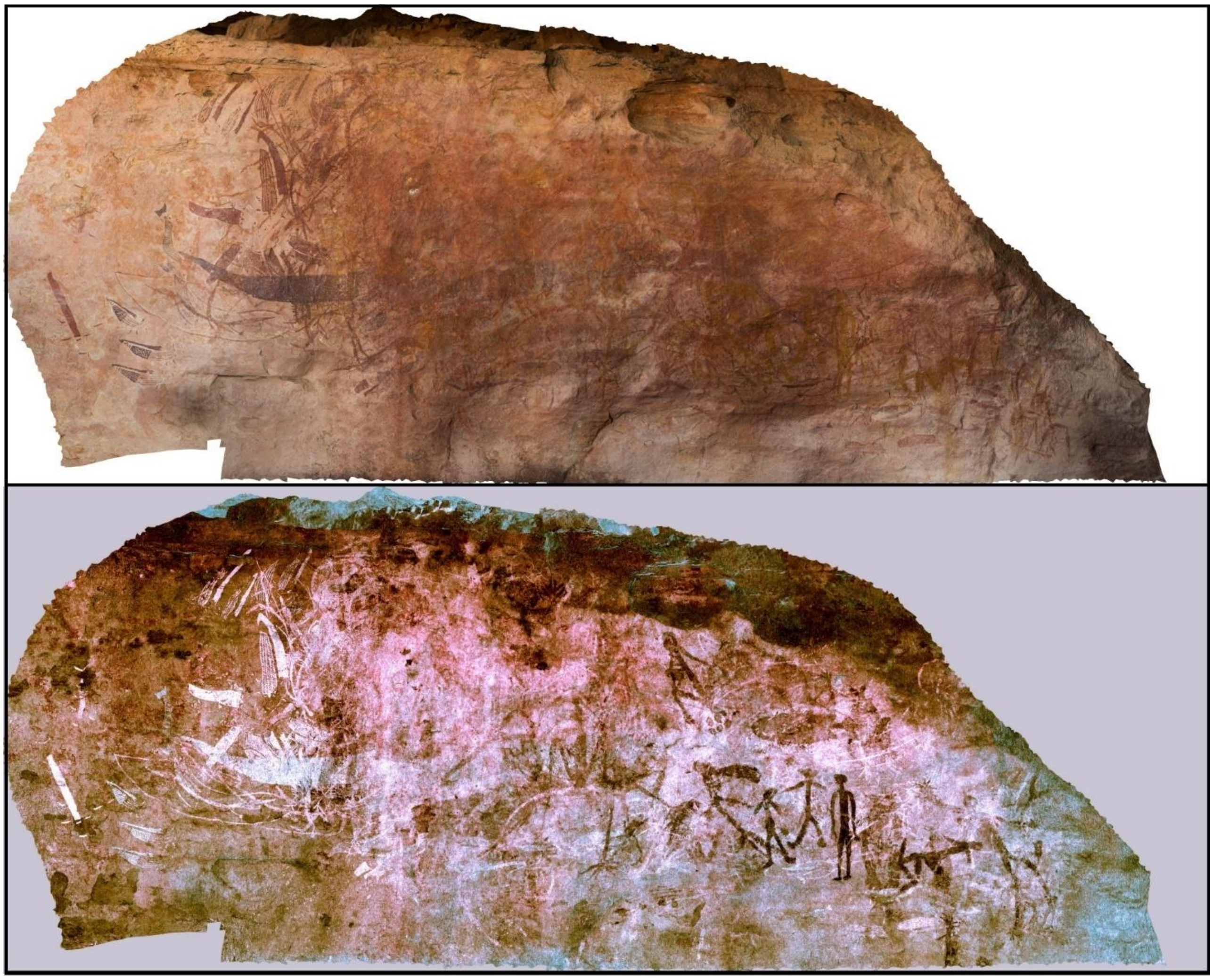


Figure 2.2 Panel before (top) and after (bottom) applying the DStrech LYE enhancement to accentuate yellow ochres.

SfM photogrammetry recording requires multiple photographs of every surface from different angles. Image capture was achieved in two major passes for each site (Figure 2.3). The first or 'far pass' is aimed at capturing the rock geometry itself. This pass aims to capture all of the surfaces of the site and will define the extent of the recorded area but does not pay particular focus on the motifs themselves. This capture is done from a distance that allows wide-scale coverage of the site, and photographs are captured gradually moving in from the extents until satisfactory overlap has been achieved covering all of the desired areas. The resolution of the images recorded is an important consideration. Whilst the first pass will image the entire surface of the site, distance and angle of view are insufficient to provide the necessary clear and distinguishable details of the motifs. The second pass focuses on the art itself. Identifying each panel and each motif is critical in achieving a detailed site record. The photographs of the second pass include close-up shots of the motifs and this is captured in a panel-by-panel approach moving left to right across the site. Image overlap is not as important for this phase as alignment is achieved based on the first pass. For larger motifs, overlapping photographs allow more pixels to be captured than a single image framed on the motif extents. For smaller motifs, framing each motif in a single photograph may provide an adequate and clear record at an acceptable resolution to clearly distinguish all the details of each motif. Similarly, as a means of recording the superimposition of the motifs, each panel should be recorded with an overlapping approach with detailed images of all of its surfaces. In this way, the resolution of the ultimate photo-merged surface can be thought of as variable and scalable to the needs of each motif. To reduce projection distortion when viewing these panels and motifs in isolation, the images are taken at as close to a 90° angle as possible.

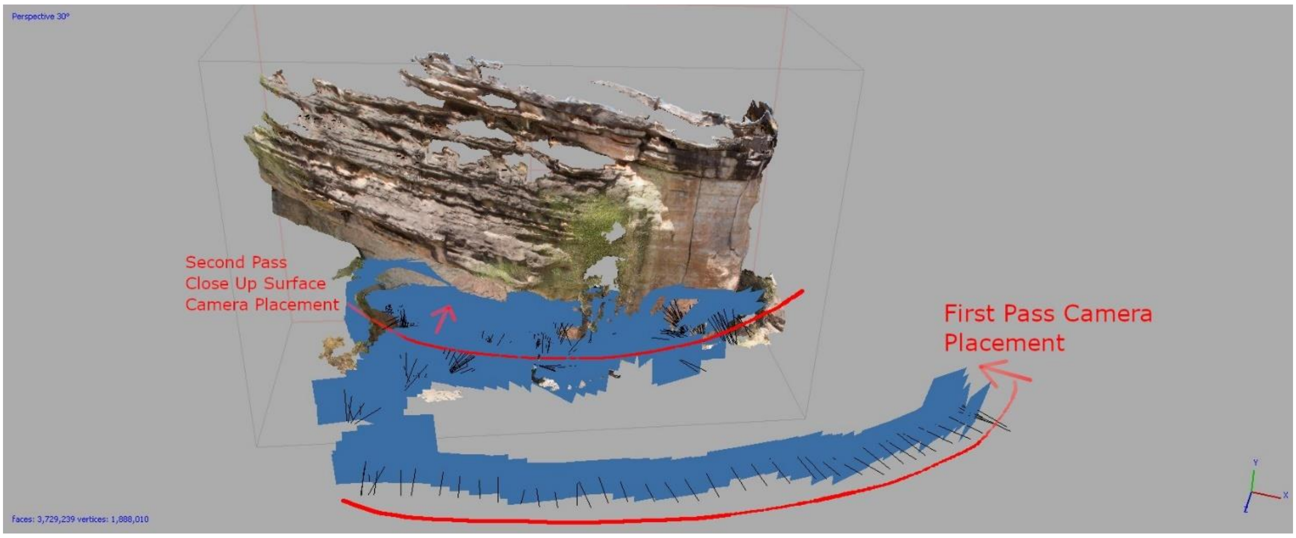


Figure 2.3 Camera placement relative to the rock art site showing the far pass and the close pass

The actual image resolution in this study varied between sites due to the use of different cameras with different technical specifications. The largest image resolution recorded by this project was 8688 pixels by 5792 pixels in a RAW image format. High-resolution images are only needed when the details that are being captured by that image require a high resolution to be clearly distinguished in the image. For this reason, the first pass aimed at capturing the overall site geometry was often recorded at a lower resolution and in a JPEG format to save memory space in the field, whereas larger formats were used for the close passes that captured motif details.

The rock art in the Wulk lagoon area has been inscribed in expansive rock shelters and surrounding open rock faces. These open outdoor environments present a number of complications to recording including issues caused by sunlight, vegetation, and the complexity of the rock geometry itself. The recording is conducted at a time when the sunlight is most evenly dispersed over the site and mottled shadows are avoided, especially in areas where motifs are visible on the rock surface. Changing lighting conditions are also a significant consideration for site recording such that any area that has been captured in one image should be captured in all subsequent images in the same lighting conditions. This, importantly, helps with both the alignment of the cameras during the post-processing phase as well as the comprehension of the model when it is viewed and interacted with.

Vegetation can have a significant impact on the model alignment and appearance. Interferences to the generation of a clear and comprehensible geometric record come from both the occlusions caused by vegetation prohibiting a record of concealed surfaces as well as the fine and dense nature of foliage. Wherever possible, obstructing foliage was cleared before image capture. Where clearing was not feasible, image capture was taken in a more intense way with a dense close-range record made of surfaces that are close to the foliage.

A final, and important, consideration is the complexity of the rock geometry itself. Rock shelters are highly erosional areas with a great deal of complexity from factors such as disconnected boulders, caverns and cracks in the rock, and deep shadow contrasting with bright light. This geometry requires individual consideration to ensure capture of all sections is achieved.

Photo targets were used as markers to aid in subsequent image alignment during post-processing and allowing rock shelter models to be aligned to drone-based landscape models using shared markers visible in both data sets. The placement of these markers was made to evenly distribute across the width of a shelter with more placement focussed on areas of complex geometry. At least three photo targets were placed in locations that will be visible in both ground-based and aerial images.

The total number of photographs used to construct the models varied between sites. Larger, more complex, sites require more photographs to capture the geometry in the large sweeping pass, and additionally, sites with a larger painted surface area require more photographs to capture at the close-range pass level. The largest number of photographs used in these recordings was 3858 images.

2.3.1 Model Processing

The digital model produced for each site was generated using Agisoft Metashape. The total processing time for each model varied based on the number of photographs used and the resolution of those images. The processing time for the models varied between a few hours in most cases and in the longest case more than 24 h. The processing was performed on a computer with 32 gigabytes of ram, NVIDIA Geforce GTX 1080 Graphics card, and Intel I7 Central Processing Unit. Model alignment, dense point cloud, and mesh generation were processed using the 'High' quality settings for each. The texture was generated using the 'generic' texture mapping mode. This texture mapping was chosen as it is able to evenly distribute the texture of the surface area of the rock shelter. The texture file produced has a resolution of 4096 (4 k) pixels (width and height). This texture is evenly distributed over the entire surface area of the mesh. This does not result in a detailed texture for the motifs themselves and the quality will be increasingly poor with an increased surface area. To achieve a detailed texture for the motifs, the model (Figure 2.4a) was divided into panels (Figure 2.4b, d) that represented discrete and relatively flat areas where motifs had been inscribed. Mesh faces that made up panel sections were extracted into separate chunks and treated as an independent model for texture generation. The panels were textured again with 4 k resolution before being merged with the shelter mode (Figure 2.4c). This way the unpainted rock surfaces and each painted panel were independently textured at 4 k resolution giving painted images enough resolution to be clearly visible in the final model (as shown in Figure 2.5).

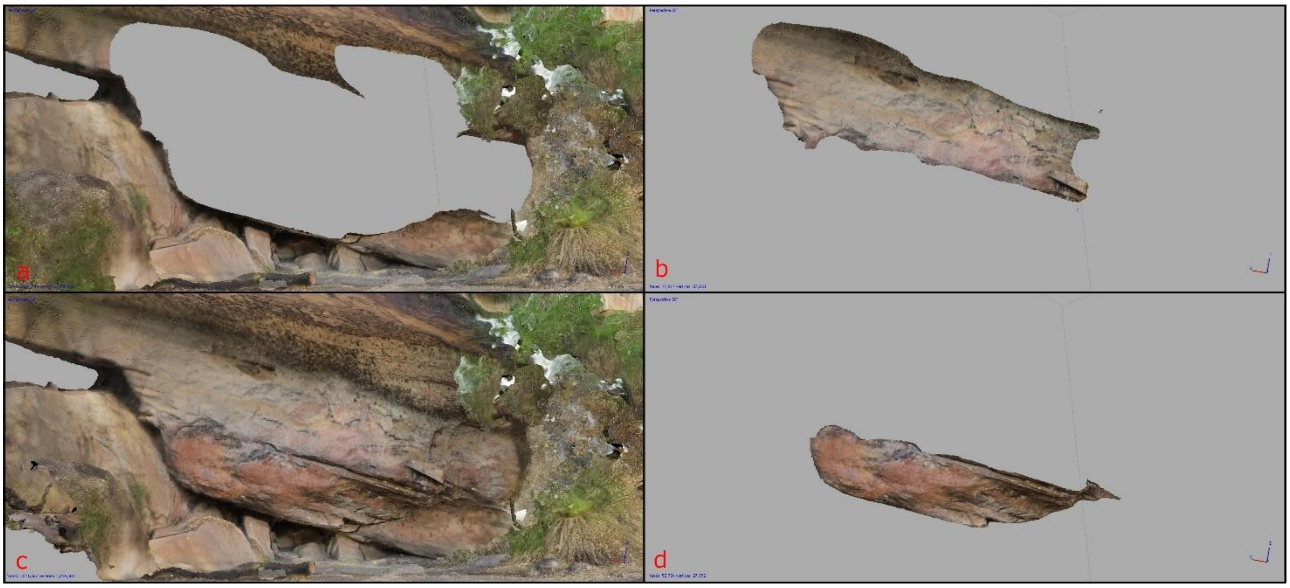


Figure 2.4 Original model with panels individually extracted (a), individual panels (b, d), the final model with separately textured panels merged back into one mesh (c)

Figure 2.5 Original photo (left). Texture fit to full geometry (middle). Texture fit to panel (right)

Because the textures are generated directly from the underlying images used to align the model, these images can be altered with the DStrech program after model generation to accentuate different ochre colours. This image can then be used to texture the underlying model as long as identical photographs were used, with no changes to their file names or their dimensions. Figure 2.6 shows the same site model textured with both original photographs and the same photographs with the DStretch LYE enhancement which accentuates the almost invisible yellow pigments on the site.

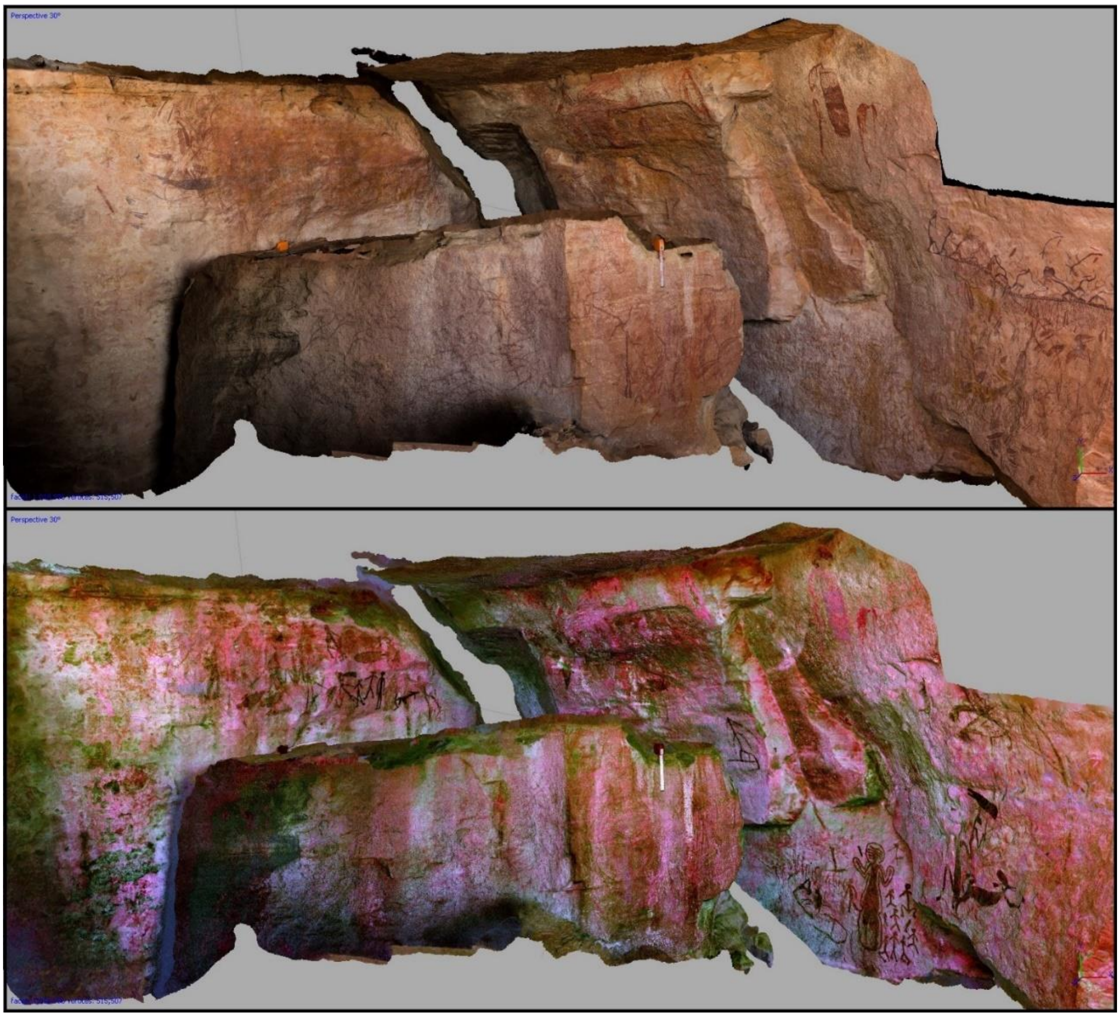


Figure 2.6 Rock art site model textured from RGP photographs (top) and DStretch LYE enhanced

To georeference the models, the markers placed in the scene were given position and scale information. This information was derived from a total-station survey geolocated using a static GPS position recorded on the site. The GPS position was post-processed using the AUSPOS service and was provided in a geographic coordinate space using eastings and northings and elevations in the Australian Height Datum. For subsequent recordings of these sites, the models were aligned and scaled using the models generated in the first survey (2015) as a reference. This alignment was conducted with the ‘Align Chunks’ point-based alignment function within the Agisoft Metashape software. As the 2015 models were georeferenced using a Total Station survey and Static GPS Positions, this quality of georeferences was made available to the subsequent models generated in 2019 using this alignment method.

To georeference the models of sites that weren’t recorded in conjunction with a Total Station survey, shared markers were used between the aerial photography captured with the drone and the rock shelter photogrammetry models. The aerial photography was georeferenced firstly with the onboard GPS with low accuracy and secondly fit to recognisable features in landscape satellite imagery.

By using aerial photography to georeference SfM photogrammetry models, it was possible to avoid undertaking a total-station survey for difficult-to-access locations in subsequent revisits. This is beneficial in reducing the recording time and cost of equipment used. A large-scale aerial photography survey was conducted over the landscape using a DJI Mavic 2 Pro drone and an Event 38 E384 unmanned aerial vehicle (UAV) mapping drone to provide a total coverage of 18.14 km2, which covers the entire study area. This survey recorded ground control points which were measured with an Emlid RS + RTK GNSS or a CHC X90 + static GPS to georeference the resulting digital elevation model and orthophoto. This serves as a model to align future drone surveys and provide an accurate georeference. By placing markers that are captured by both drone survey and ground-based photogrammetry, new recordings can be conducted and effectively georeferenced without the need to bring heavy and expensive survey equipment. Figure 2.7 shows the Digital Elevation Model produced by the extensive aerial survey. This process was used for one new site recording in 2019 and will be the procedure for future site recordings within the coverage of this aerial survey.

In addition to the textured models produced from the ground-based photogrammetry, Metashape was also used to produce high-resolution orthomosaic images of each painted panel from each recorded site. Orthomosaic images (Figure 2.8) are composite images formed from combining the original captured images that overlap a representative surface in the model. As the photo locations are known, the mosaic images can be produced with a seamless transition so long as photographic clarity and lighting are maintained as closely as possible between images. Such a photomosaic is, however, a projection of the surface as it is a two-dimensional representation of the three-dimensional surface. Photomosaics were generated for each panel by positioning a camera as close to 90° to the flattest rotation of the panel to minimise any projection distortion. Panels with a great deal of curvature are required to be projected several times to maintain an undistorted perspective in the orthomosaic images produced.

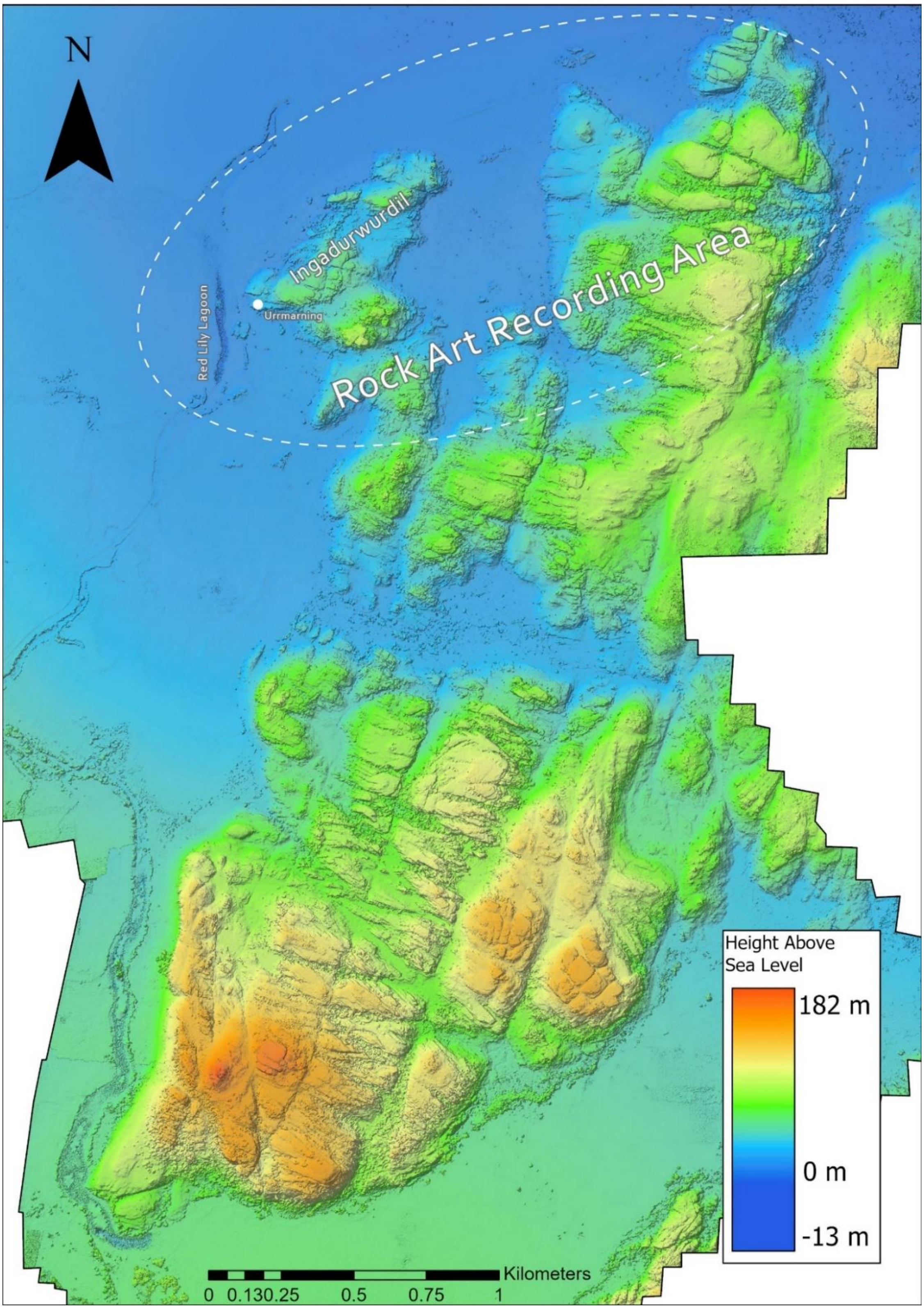


Figure 2.7 GRLLA study area digital elevation model derived from drone-based aerial photogrammetric recording

Figure 2.8 Orthomosaic panel showing Northern Running Figures

2.4 Data Hosting and Virtual Accessibility

The GRLLA sites were recorded to satisfy a variety of purposes including management, research, community access, and engagement, as is common for rock art studies (Cassidy et al. 2019). Rock art is a cultural artefact and belongs to the Traditional Owners and descendant community who live and manage the country in which it is situated. Rock art has contemporary cultural value and is impacted by a social framework and cultural protocols that manage site access and information about associated stories. This is true of physical places as well as virtual spaces that represent these places. This diversity of use means that choosing how these data are stored, curated, and accessed is challenging. To satisfy these many purposes as well as cultural protocols that govern this access, a web-based approach has been chosen using a purpose-built website (DigitalRockart.com.au 2020). This website was developed with the aim of both providing password-limited access to the data produced as well as explaining the methods used to capture the data. This management approach to virtual cultural spaces follows the directions visible in modern Indigenous cultural database management systems (Cohen et al. 2010; Gibson 2007; Smith et al. 2013) but with a particular focus on the nuances that come with highly immersive virtual spaces (Brown and Nicholas 2012).

Web hosting is an advantageous means of sharing such data as it provides password-protected access without the need for proprietary software or extensive computer power. Whilst the website manages the data access, Sketchfab was used to host the 3D models in a web-based platform. Sketchfab was used as it allows 3D model viewing and web-page embedding of the 3D model inspection window. Sketchfab importantly provides optional password protection to uploaded models. This allows the privacy of a model to be controlled whilst using this web-accessible platform. Sketchfab also provides support for virtual reality (VR) interaction with any uploaded 3D models. This allows any 3D model to be viewed using a smartphone housed in a virtual reality (VR) head mount. Alternatively, a purpose-built VR system such as Oculus Rift or Vive can view the model using the embedded Sketchfab model. As part of this research, two VR smartphone head mounts were provided to the Njanjma Rangers to facilitate community interaction with the virtual spaces representing the sites recorded in 3D.

The benefits of remote site access are important when considered in the context of remote indigenous communities. The effects of colonisation have led to continued socio-economic disadvantage and health inequality for Australian Aboriginal and Torres Strait Islander communities (AIHW 2017). As chronic diseases such as asthma, diabetes, cancer, and heart disease are more prevalent in Indigenous communities, a reduction in physical activity occurs which can inhibit participation in social and cultural activities (Bailie et al. 2015). The rock art sites in the GRLLA are particularly difficult to access for people with limited mobility, and so remote virtual sites can improve accessibility and support the continuation of cultural activities in this region, with a demonstrated positive impact on wellbeing (Taçon and Baker 2019). This fits into a broader movement to use digital cultural-heritage techniques to support Indigenous Australians (Moffat et al. 2016; Wallis et al. 2008) through collaborative archaeologies (Smith et al. 2019a).

2.4.1 Limitations and Challenges

The methodology developed for this study has faced a number of challenges in the recording and subsequent data management processes that proceed field recordings. This methodology has been developed iteratively through the process of repeated subsequent recording efforts and data management and post-processing throughout the five-year lifespan of this work. Many nuanced issues were discovered and addressed throughout the study and have been retroactively added to the methodology described above. These include the issues of recording around vegetation, in lower light conditions, multiple passes to capture image detail, and the geolocation of ground-based site models using drone-based models. However, there are several limitations and challenges that are still present in the described methodology.

Foremost, the methods described and developed require a high level of technical expertise and in some cases considerable equipment cost. Whilst SfM photogrammetry is a relatively low cost recording method and only requires a hand held camera, tape measure, and printed aerial targets, the post-processing does require computer hardware that increases the overall cost of the method. Additionally, the Agisoft software and licencing prices add considerably to the overall cost of the methodology. Equipment costs may be reduced with the use of cheaper cameras or mobile phone cameras, provided they can adequately capture the details of the rock art. However, to undertake recordings in the fashion described would require an upfront investment of approximately AU$6,099 in equipment and AU$200 in annual costs for data hosting and visualisation.

Sketchfab adds an additional cost to this methodology as it has a subscription cost in order to expand its monthly upload limit from one model per month, which is offered for the free use of the website, to 30 uploads per month with the ability to add password protection to these models. Sketchfab offers unlimited model uploads for downloadable models; however, this option has not been selected, so as to impose individual site access restrictions to different models. By making models view only and not downloadable, the Rangers and Traditional Owners have the option of making models temporarily available to the public or a specific group and changing this access in the future without the possibility of that model being downloaded or otherwise duplicated. A continual subscription fee is required to gain the benefits of this service. Should the account cancel this subscription, private models will remain private and can be accessed again once subscription is renewed. Sketchfab also imposes a file size limit which can limit the size of individual models to 200 megabytes. This may further limit the size of models being uploaded. This can be a challenge and require the models created for this purpose to limit the number of faces and texture sizes used especially for larger sites. Another solution is to split the site record into two separate models if face count and texture size reduction are not possible.

The website used to manage user access to the different Sketchfab models and allow data to be digitally curated also adds both a technical expertise requirement for such web development to this methodology as well as requiring a server to host this website which is an additional cost over time.

Despite these limitations and costs, this web-based method of data storage and access control offers a robust, flexible, and safe way for the management of cultural heritage materials that would otherwise require physical storage on hard drives which severely limits access possibilities.

2.5 Discussion

The methodology used for recording, curating, and displaying the rock art sites of the Wulk Lagoon area has been designed to satisfy the requirements of archaeological survey, cultural-heritage management, and community engagement and interaction. By creating products with multiple purposes, the digital 3D approach satisfies a broad range of interests in recording these important sites. This project considers a 3D approach as not ending with the creation of a 3D record but also incorporating the accessibility and management of such digital spaces.

A benefit of SfM photogrammetry is rapid site recording using low cost and lightweight equipment. This articulates well with a broader scale survey using UAVs to provide coverage to locate additional sites in the area. This approach allows future site recording to be conducted with a hand-held camera, portable measuring tape for scale, and a drone for landscape context capture. This achieves the goal of low cost and easy-to-transport equipment. One limitation of this approach is the requisite technical expertise in the photogrammetric recording process. This process has so far been conducted by archaeologists and spatial survey experts. However, future training and development programs are being conducted to equip the Njanjma Rangers with the expertise and equipment to continue these recording methods independently with site revisits. It is also notable that where a site revisit has occurred individual images can be aligned to the existing models and compared for changes. This reduces the need for full-site modelling to be performed with every revisit to conduct change detection and site monitoring.

The use of Sketchfab integration to a website that can be controlled by NAC and Traditional Owners to curate this digital collection is one example of the robust usability of the highly detailed 3D models produced. This work has extended the use of these 3D applications from simply a visual record into useful products for site management, virtual site access to the community, and to ongoing archaeological analysis. The use of these virtual records may extend to tourism and the integration of models with other information such as ambient sounds, and recorded audio information about the sites is possible.

2.6 Conclusion

This paper presents a methodology for the digital recording of rock art using SfM photogrammetry that has created a high-resolution, immersive product suitable for cultural heritage management, archaeological research, and community engagement from a number of sites in the Greater Red Lily Lagoon Area of Northern Australia. In all cases, the sites, both physically and virtually, remain in the management and care of their Traditional Owners, allowing the effective management of these important sites in new ways within a digital cultural space.

2.7 Acknowledgements

Thanks to Njajma Rangers, Alfred Nayinggul, Kenneth Mangiru, Anita Nayinggul, Katie Nayinggul, Manbiyarra (Grant) Nayinggul, Tex Badari, Sebastian Nagurrgurrba, Hilton Garnarradj, Jacob (Junior) Nayinggul, Lawrence Nayinggul, James Dempsey, Ursula Badari, Timothy Djumburri, Thomas Falck, Daniel McLoney, and Shay Wrigglesworth who provided invaluable assistance in carrying out this research. This research was supported by Australian Research Council grants DE160100703 (Moffat), DE170101447 (Wesley), and FT170100025 and DE140100254 (Aubert); by George Chaloupka Fellowships to Moffat, Jones, and Wesley; by a National Geographic Grant to Wesley and Jones; and by a Flinders University Early Career Researcher Impact Seed Grant to Moffat.

CHAPTER THREE

Chapter 3: Reconstructing rock art chronology with transfer learning: A case study from Arnhem Land, Australia

An earlier version of this chapter was published in *Australian Archaeology:* Jarrad Kowlessar, James Keal, Daryl Wesley, Ian Moffat, Dudley Lawrence, Abraham Weson, Alfred Nayinggul & Mimal Land Management Aboriginal Corporation 2021 Reconstructing rock art chronology with transfer learning: A case study from Arnhem Land, Australia. *Australian Archaeology* 87(2): 115–126.

Approximate contribution of co-authors: Jarrad Kowlessar (65%), James Keal (5%), Daryl Wesley (5%), Ian Moffat (5%), Dudley Lawrence (5%), Abraham Weson (5%), Alfred Nayinggul (5%) & Mimal Land Management Aboriginal Corporation (5%).

3.1 Abstract

In recent years, machine learning approaches have been used to classify and extract style from media and have been used to reinforce known chronologies from classical art history. In this work we employ the first ever machine learning analysis of Australian rock art using a data efficient transfer learning approach to identify features suitable for distinguishing styles of rock art. These features are evaluated in a one-shot learning setting. Results demonstrate that known Arnhem Land rock art styles can be resolved without knowledge of prior groupings. We then analyse the activation space of learned features and report on the relationships between styles, arranging these classes into a stylistic chronology based on distance within the activation space. By generating a stylistic chronology, it is shown that the model is sensitive to both temporal and spatial patterns in the distribution of rock art in the Arnhem Land Plateau region. More broadly, this approach is ideally suited to evaluating style within any material culture assemblage, and overcomes the common constraint of small training data sets in archaeological machine learning studies.

3.2 Introduction

The Arnhem Land Plateau region of northern Australia has a rich and detailed history of rock art inscriptions (Chaloupka 1993) (Figure 3.1). The earliest dated pictograph in this region was inscribed around 28,000 years ago (David et al. 2013a) and human occupation has been dated to 65,000 years ago (Clarkson et al. 2017). With the practice of rock art production continuing through to the current time, the longevity of this artistic culture speaks to the complexity and diversity of artistic styles observed across this landscape. The frequency of paintings along with their stylistic diversity in the context of the deep history of human activity has created a great challenge for those wishing to unravel the antiquity of the region’s art (Chippindale and Taçon 1998).

This challenge is further complicated by the limited availability of rock art for which direct dating methods can be applied (Jones et al. 2017b). In cases of repeated site usage, the chronology of the art can be derived from relative sequences in the superimposition, with older motifs appearing beneath newer. This method of investigation can also be supplemented with inferences drawn from environmental and technological details depicted in the art (Chaloupka 1993; Chippindale and Taçon 1998; Lewis 1988). For the majority of rock art, however, evidence sufficient to pinpoint the time of inscription does not exist.

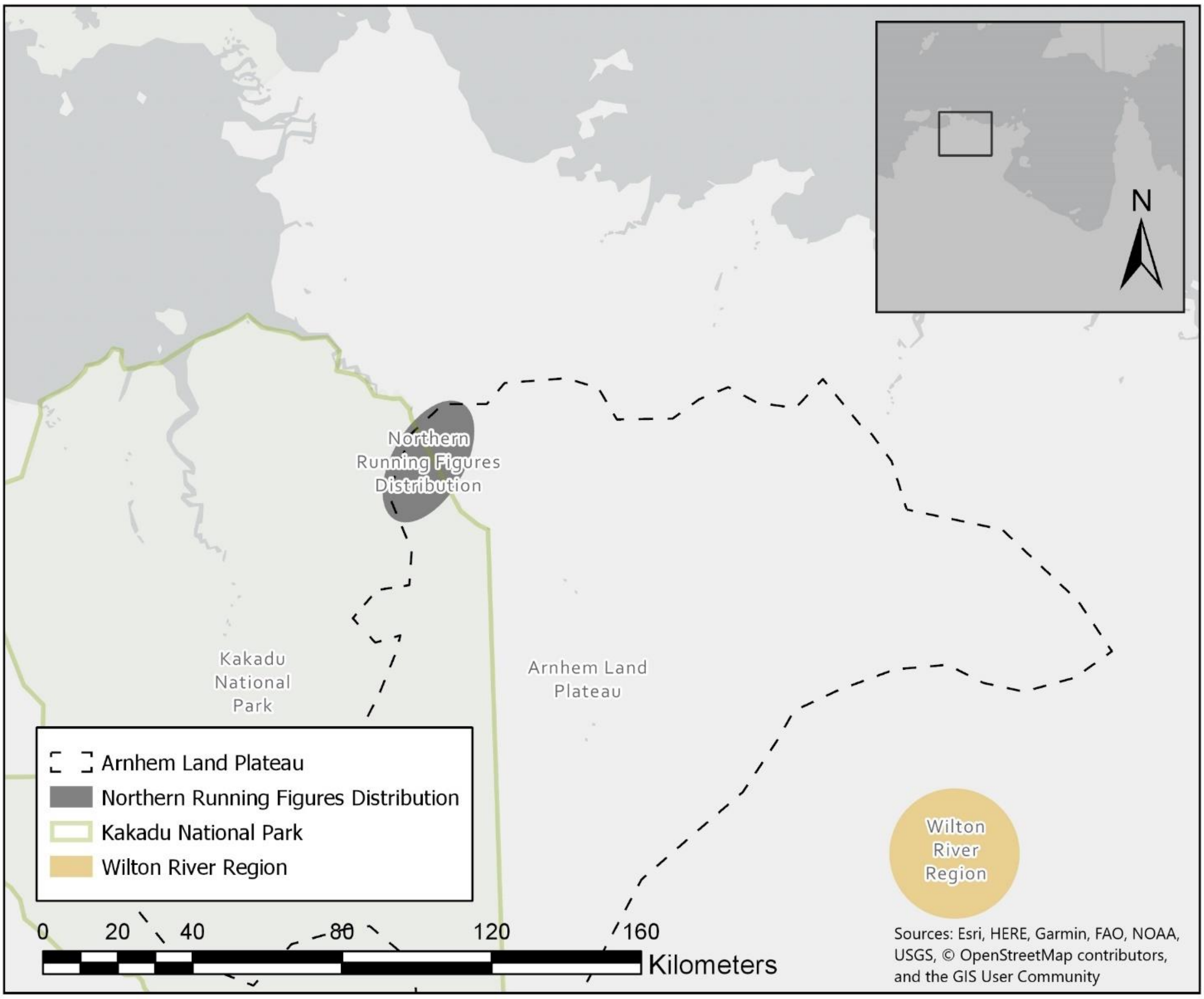


Figure 3.1 Map of the Arnhem Land plateau rock art region highlighting the extents of the pan-Arnhem data sources as well as the geographically isolated distributions of the Northern Running Figures and the Wilton River motifs.

Style is an ever-present attribute of how different items of material culture relate to one another. However, classifying style and quantifying stylistic relationships are time-consuming challenges in the field of archaeology, particularly rock art studies (Schaafsma 1985). The rock art assemblage of the Arnhem Land Plateau region is stylistically diverse and has long been the focus of archaeological debate. By organising the assemblage into distinct styles, archaeologists seek to understand the chronological evolution of art in the region. These styles are difficult to define and even more difficult to organise into a relative sequence. The complexity of rich and nuanced information encoded in style is central to the study of archaeology (Conkey and Hastorf 1990). Style is the variation in material culture over time and space which occurs when human activity is conducted in a particular way and in the context of alternative ways (Clegg 1987; Hegmon 1992). Following this definition, 'stylistic behaviour is founded on the basic human cognitive process of identification via comparison' (Wiessner 1984: 190) and therefore any study of style is a study of the differences between styles. Style must also have both geographic and temporal controls, as does the social identity of the group of people for which a given style is characteristic (Sackett 1982).

In the context of art, when style is considered in this way, there are many disparate factors that could each describe style or could be combined to form different definitions of style. These factors include the subject matter being depicted (e.g. human figures, flora and fauna, geometric designs), different use of colours and design elements, placement and display of the subject (e.g. arrangement of the art in the depiction, the type of material on which the art is inscribed) and the method used to inscribe the art (brush work, line thickness, use of stencilling) (Domingo Sanz and Fiore 2014). Variations in any one or more of these elements could be used to describe stylistic classes (Domingo Sanz and Fiore 2014: 7105). The application of stylistic analysis to rock art has been, and continues to be, critical in unravelling the overlapping history of graphic illustration in northern Australia (Layton 1992).

3.2.1 Observational approaches

Connoisseurship has proven to be one of the most effective means of detecting stylistic categories in rock art and forming those categories into larger movements or periods (Gunn et al. 2018; Gunn 2018). In this method styles are first defined by typological factors inferred by visual inspection of repeated motif patterns (Chaloupka 1993; Lewis 1988), after which they may be further organised into an inferred chronological order. A major concern for archaeological research in Arnhem Land has been the divisive chronological schema for styles of rock art. There have been competing rock art chronologies proposed for Arnhem Land each consisting of some variation on stylistic definitions (Brandl 1973; Chaloupka 1993; Chippindale and Taçon 1998; Haskovec 1992; Lewis 1988). These chronologies are strongly dependent on the identification of stylistic classes, technology and subject matter depicted in the rock art and subsequent superimposition. These competing relative chronological systems are therefore dependent on reliably identifying these characteristics within an assemblage of rock art.

Brandl (1973) produced one of the first detailed attempts at developing a chronology for Arnhem Land rock art with the introduction of eight stylistic periods. Brandl's (1973) styles became the basis for the chronology and styles later developed by Lewis (1988: 107). The chronology developed by Lewis (1988:ix) consists of four major periods delineated by changes in material culture. These are known as the Boomerang, Hooked Stick, Broad Spearthrower, and Long Spearthrower Periods which have been named after the most distinctive material culture associated with each era (Lewis 1988:105). Lewis' (1988:13) methodology was based on depictions of human figures and their associated material culture items as he argued artefacts create identifiable, and therefore more reliable, temporal boundaries and criticises superimposition as a method for defining chronologies between styles (Lewis 1988:107).

In contrast Chaloupka (1993:89) anchored his proposed chronology to generalised timings coinciding with major environmental and climatic changes in Arnhem Land with periods divided into PreEstuarine, Estuarine, and Freshwater (and Contact) which contained at least 11 major styles or stylistic complexes. Lewis (1988:107) suggested that Chaloupka's Pre-Estuarine and Estuarine division does not exist and should be conflated with later periods. Chippindale and Taçon (1998) used Chaloupka's styles to build a chronology based on Old, Intermediate and New, identifying 10 major styles or stylistic complexes. Haskovec (1992:148) stated that material culture depicted in rock art changes less frequently than stylistic change. Therefore, he emphasises style should be the main approach towards identification and definition of a rock art assemblage (Haskovec 1992). To add to the chronological complexity of Arnhem Land rock art, Haskovec (1992:149) proposes six phases containing eight major styles or stylistic complexes. While there is a general acceptance for broad categories of rock art styles such as Dynamic Figures, it has been demonstrated that there is still significant variation within an overarching schema (Johnston 2017). Furthermore, the early Large Naturalistic Style has been noted as recursive in nature as large naturalistic depictions of subject matter occur throughout the Arnhem Land rock art sequence (Chippindale and Taçon 1998; Jones et al. 2020). The iterative and recursive nature of Indigenous rock art can be problematic for the identification of stylistic chronologies in Arnhem Land (Morphy 2012).

In this work we examine styles associated with the depiction of human figures. Chaloupka (1984, 1993) described several styles of human figure depictions found in the Arnhem Land region. They are, in interpreted chronological order: Large Naturalistic Figures, Dynamic Figures, PostDynamic Figures, Northern Running Figures, and Simple Figures with Boomerangs. These styles are characterised using a variety of parameters including the complexity of lines used, patterns that fill the voids of the image, and the posture or activities typically depicted. The chronology put forth by Chaloupka has found broad agreement despite some challenges regarding superimposition and technological material culture associations (Lewis 1988). The geographic scale of this chronology, as well as its sensitivity to more nuanced styles, are poorly defined within these broad categories (Johnston 2017). For example, Chaloupka suggested that four distinct stylistic phases occur within the Dynamic Figures class, each represented as a minor variation in the style of depiction. Other researchers have argued that minor changes within Dynamic Figures are not evidence of more nuanced stylistic phases, however, can instead be explained by individual artistic expression (Johnston 2017).

This debate raises the important question of how a distinct style should be defined. How major must a typological change be, and at what frequency must it occur, for it to be considered a new style? This also raises geographic questions about how regionalisation might affect motif style, even when these motifs still fit within existing broad styles. This research aims to provide insight into these questions through the use of machine learning methods to quantify style and locate it on a relative stylistic continuum.

3.2.2 Statistical approaches

Observational approaches to style identification have been extended to incorporate various statistical analyses (Travers and Ross 2016, 2017). These analyses are based on the measurement of artistic attributes identified by the researcher as important to classifying style. These approaches have proven effective in identifying patterns within the data that relate to style, as well as smaller patterns which can occur within an identified style, such as the changing use of technology and the social role of artefacts within the societies producing the art (Travers and Ross 2016, 2017). A recent technique called Geometric Morphometrics (GM) has been used to identify animal species in rock art motifs (Cobden et al. 2017). The approach locates the coordinates of features that are key to identifying species from known images and compares the relative geometric features in known and unknown depictions. This approach attempts to reduce researcher bias and make a mathematical comparison of the geometry of individual figures. Like the traditional statistical methodology, this approach relies on the identification of geometrically and biologically meaningful features in the data (Cobden et al. 2017). The approach is also supervised by classes defined by the researcher. This requires that the same features being identified are purposefully depicted by the original painter in the art, as opposed to a stylistic means of encoding species information that is unknown to the researcher. In this way statistical approaches to rock art style analysis are effective at identifying and quantifying known attributes, however these approaches remain unreceptive to the detection of unknown stylistic attributes.

3.2.3 Machine learning approaches

Machine learning approaches have been applied in archaeological context for object detection and more recently for stylistic analysis (Cintas et al. 2020; Hörr et al. 2014; Tsigkas et al. 2020; Wang et al. 2017). Recent research efforts into computer vision and machine learning have shown the ability of learning algorithms to discriminate between stylistic categories of painted art, with reasonable accuracy (Karayev et al. 2014; Saleh et al. 2016; Shamir et al. 2010). However, applying machine learning approaches to the classification of Australian rock art is particularly challenging, due in part to the limited amount of data available to individual researchers. As such, any machine learning approach suitable for analysing rock art must be capable of learning meaningful features from a small dataset, consisting of only a few examples, or without training using rock art at all.

In practice, machine learning with limited domain data can be achieved using transfer learning. Transfer learning involves taking a model developed for one task and reusing it for a second task (Caruana 1997). The tasks may differ in problem domain, datasets, or both. The success of the approach is dependent on similarities between the two tasks, and on how related the datasets are. An initial training phase is performed using background data, with any further training on the evaluation dataset referred to as 'fine-tuning'. For image analysis, transfer learning relies on the reuse of learned features that are common in image datasets, such as edges, corners, and other geometric structures comprised of the spatial arrangement of pixel values.

In this work we experiment with three models trained to classify images. We explore the viability of different background data by training each of the models on three well-established image classification datasets. We then assess each trained model's applicability for analysing a dataset of rock art from Arnhem Land, northern Australia. We do this without necessitating retraining, which is largely impossible due to the limited availability of data, by evaluating the trained models in a one-shot learning setting. In one-shot learning, a model must correctly predict an image's class given only one example of each possible class with which to compare it (Bromley et al. 1993; Fei-Fei et al. 2006; Koch et al. 2015; Lake et al. 2011). In this way, we demonstrate each model's impressive ability to classify examples of rock art into predefined stylistic groupings without any fine-tuning.

Successfully classifying style does not conclude the analysis of the archaeologist. The more important question is what machine learning may tell us about how the identified styles relate to one another. If an algorithm can classify style, it implies that the machine has learned an internal representation that encodes relevant discriminative features through its visual analysis of the paintings. It follows that an analysis of the learned feature space of such an algorithm is, in essence, an analysis of the space of artistic style in the data. This has been demonstrated in the domain of classical art through an analysis of the activation space preceding a classifier's output layer (Elgammal et al. 2018). This activation space describes a vector that represents the strength of activation across all the neurons of that layer. A visualisation of this activation space was able to portray the relative distances between stylistic groupings and even a correlation with the chronological order in which they were created.

Considering this, we go on to analyse our trained image encoding networks by visualising the stylistic clustering of Arnhem Plateau rock art in the activation space of encoded images. We quantify the stylistic distance between clusters, ultimately organising the styles into a single dimensional space which can be interpreted as a stylistic spectrum. If similarity in style is to be attributed to spatiotemporal proximity, then this stylistic spectrum may also implicate a relative inscription chronology. This approach to analysing style using learned representations has the potential to enhance our understanding in a wide range of archaeological applications.

3.3 Materials and method

3.3.1 Ethics

All work was conducted with approval from the Social and Behavioural Research Ethics Committee (SBREC) at Flinders University (project number 7704). Approval for this research was also provided by Marrku Traditional Owners who were present during all data collection and recording conducted on Marrku land. All necessary permits were obtained for the described study from the Northern Land Council, which complied with all relevant regulations and agreements with Traditional Owner communities for the field recordings conducted in Arnhem Land.

3.3.2 Models

Network architecture has a significant role to play in the discrimination of image features. Transfer learning has never been applied to the domain of rock art so it is not initially clear which network architecture will have the best results at image classification with ’style’ as a focussed internal metric. For this reason we considered a range of recent convolutional architectures as image encoders: AlexNet (Krizhevsky 2014), VGG (Simonyan and Zisserman 2014), and ResNet (He et al. 2016). All three networks were reconstructed as described in their respective papers, trained, then had their final layers removed.

3.3.3 Background data

The data used for training has a significant impact on the learning achieved by any of the given networks. Whilst each may be able to classify the data sets they have been trained on, the learned features used for this classification will differ. For this reason different datasets may learn features that are more or less applicable to the rock art domain. To better understand what type of image data might produce the most transferable learned features useful to distinguishing rock art styles, a number of different datasets were selected and used for background training data. The three background datasets used for training were MNIST, Quick Draw and ImageNet. The MNIST dataset is comprised of 70,000 handwritten digits. These digits have been drawn by hundreds of different people and so many variations exist within the basic form of each of the 10 digit characters.

This robust data set has been used for successful learning based classification since 1998 (LeCun et al. 1998). The images in the MINIST dataset were originally 28 by 28 pixels and were scaled to the input size of 224 by 224 pixels required by the chosen network architectures. This dataset was selected as a transfer learning candidate due to its parallels to the hand drawn figures in the primary dataset represented in monochromatic drawn lines. The Quick Draw dataset is a collection of 50 million drawings across 345 conceptual categories such as ‘face’, ‘pizza’, and ‘fire hydrant’ (Ha and

Eck 2017). In contrast to MNIST, drawings in the Quick Draw dataset are pictographic, resulting in considerably more variation across any given category. Drawings were originally captured as timestamped vectors but for our purposes timing information was removed. Vectors were positioned and scaled to fill a 224 × 224 region, simplified using the Ramer–Douglas–Peucker algorithm with an epsilon value of 2.0, then rasterised with a stroke thickness of 16 pixels. Background and evaluation datasets were formed by randomly sampling 1000 images from each class.

Finally, we considered ImageNet, an image database organised according to concepts in the WordNet hierarchy (Deng et al. 2009). Currently, ImageNet provides an average of over 500 images per concept, each of which are quality controlled and human-annotated. In this work we did not handle ImageNet data directly. Rather, we made use of model parameters resulting from training a classifier on 1000 ImageNet concepts. Parameters were provided by the software package PyTorch (Paszke et al. 2017). ImageNet differs from the other two datasets in that it comprises photographs with three colour channels rather than binary masks or hand drawn representations.

3.3.4 Training

Training batches were formed by randomly sampling 64 images from a given training dataset. Irrespective of the dataset, an epoch was defined to comprise 100 batches. To determine loss, we imposed a cross-entropy objective to each classifier. This objective was combined with the standard back-propagation algorithm. The Adam optimisation algorithm (Kingma and Ba 2014) was applied with a learning rate of 1×10^{-4}. Weight decay regularisation was not used. The learning rate was reduced by a factor of 10 every time 10 epochs passed without observing a reduction in training loss. Training was terminated when the learning rate dropped below 1×10^{-8}. No training was performed using the primary rock art dataset.

3.3.5 Application to rock art

A primary data set was formed of Arnhem Plateau rock art from a variety of sources. A total of 98 motifs were sourced, each of which depicted a single human figure from one of six known stylistic classes: Dynamic Figures (DF), Post-Dynamic Figures (PDF), Northern Running Figures (NRF), Simple Figures with Boomerangs (SFWB), Simple Figures with Round Headdresses (RH), and Wilton River Region Simple Figures (SFWR). These classes were populated with examples both from published literature sources and from photographs taken of the rock art directly. The classes chosen represent motif styles observed throughout Arnhem Land with the exception of the Northern Running figures which have an observed distribution limited to a small area on the northwestern corner of the Arnhem Plateau (Jones and May 2017; May et al. 2018).

The motifs gathered from photographs for this study are from the Wilton River Region of central Arnhem Land as part of an ongoing research project. Table 1 shows the classes chosen and the data source for each class. The classes chosen from the Wilton River Region were included to provide a geographical study area that falls outside of the areas represented by published sources. Figure 3.1 shows the Wilton River region and the location of the Northern Running Figure distribution relative to the Arnhem Plateau. Since the images in the primary dataset were gathered from multiple sources, they were first standardised. All images were traced to produce masked representations with no associated colour information. This also removed any rock surface information from consideration. All tracings were oriented so that the depicted figure was approximately upright and then zero-padded until square. Finally, the images were scaled to be 224 × 224 pixels in size. It should be noted that processing the images in this way discarded relative scale, rotation and colour information from the data that may have been pertinent to classifying style. We do not propose a solution to this limitation in the current work.

Table 3.1 Summary of the primary dataset formed from various sources.

Acr.	Style	Source	Image count
DF	Dynamic Figures	(Chaloupka 1984, 1993; Chaloupka pers. comm.; May et al. 2018)	16
PDF	Post-Dynamic Figures	Marrku Traditional Owners	16
NRF	Northern Running Figures	Chaloupka 1993	16
SFWB	Simple Figures with Boomerangs	Chaloupka 1993	16
RH	Simple Figures with Round Headdress	Marrku Traditional Owners	18
SFWR	Wilton River Region Simple Figures	Marrku Traditional Owners	16

No fine tuning was performed using the rock art dataset. Rather, each convolutional encoder was used, as trained on background data, to encode rock art images into a vector space (activation space). For consistency, we chose to analyse the activation vector of the layer that follows the last convolutional layer of each network. In each case this activation vector had 4096 elements with the exception of ResNet, which had 2048 elements.

Evaluation was then performed by constructing a 6-way one-shot classification task (Bromley et al. 1993). For this, one test image and six additional images (one representing each of the known rock art styles) were chosen at random from the rock art dataset. The test image was then compared with each representative image in a pairwise manner and assigned the class of the representative image to which the network indicated the test image was most similar. Similarity was ascertained by taking the Euclidean distance between the pairs of vectors, with the vectors that were the least distant taken to be the most similar. The assigned class was compared with the test image's true class and this process was repeated to find the overall accuracy of each network when trained on each background dataset. Evaluation was performed on 25% of the data set. As a benchmark, the validation process was also conducted using raw pixel data from each image and the same after dimensionality reduction using PCA.

3.3.6 Analysis

Our analyses focussed on understanding and visualising the activation space of encoded rock art images. To help understand this space we visualise rock art in the activation space of the most accurate model by mapping it onto a single dimension. For this we used t-distributed stochastic neighbour embedding (t-SNE) (Van der Maaten and Hinton 2008) for its ability to reduce dimensionality while maintaining the spatial relationships present in the original high dimensional space. This restructures the artwork representations into an inferred stylistic spectrum. The t-SNE data reduction was performed 100 times to ensure the resulting ordered data was repeatedly reliable.

3.4 Results

Table 2 shows the accuracy of each encoder network model after training on each of the background datasets and then using the trained model to discern rock art styles in a one-shot setting. This accuracy score is based on the existence of known stylistic classes in the rock art data set. For comparison, a random guess achieves an accuracy of 16.67%, which all models were able to out-perform by a significant margin. Using the same nearest neighbour method but using the pixel data directly achieved an accuracy of 51.22%, which many model/dataset combinations were also able to out-perform. As a final comparison, the same method was applied to the pixel data after reducing their dimensionality using PCA to 98 dimensions, as dictated by the number of images in the dataset, achieving an accuracy of 43.00%.

Table 3.2 The accuracy of each encoder model after training on each background dataset when discerning rock art style in a one-shot setting.

	MNIST(%)	**Quick draw (%)**	**ImageNet (%)**
KochNet	38.60	49.21	-
AlexNet	43.22	49.96	72.92
VGG	42.00	54.01	69.86
ResNet	51.64	63.22	68.51

Figure 3.2 shows the results of t-SNE dimensionality reduction of the rock art data embedded in the activation space of the AlexNet model trained on ImageNet data. The dimensionality is reduced to a single dimension on the x-axis. Classes are artificially separated on the y-axis for ease of

interpretation. Each class's mean is represented by a diamond while circular data points represent the class members. The order of the class means was consistent 100 out of 100 times when this activation space was reduced using t-SNE. Only minor variations in the placement of class outliers were observed in these 100 t-SNE iterations. Across the dataset of embedded images, the variance in each vector dimension was calculated. 25% of the total variance was accounted for by the 442 most dominant dimensions, 50% by 1212, and 75% by 2310. This indicates that the embedded vectors are not dominated by only a few dimensions.

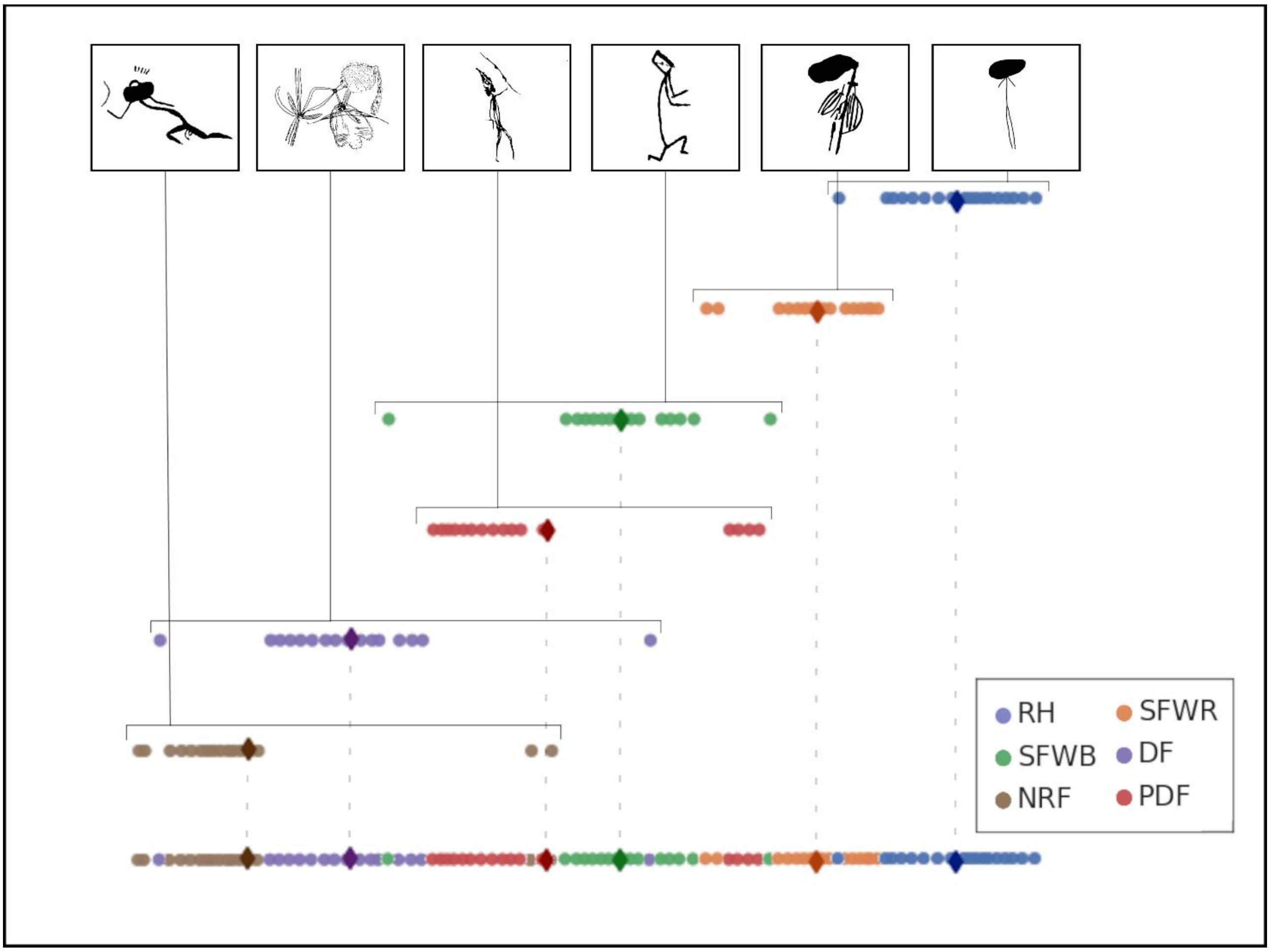


Figure 3.2 Rock art data embedded in the AlexNet/ImageNet activation space reduced to single dimension on the x-axis using the t-SNE method. Classes are separated on the y-axis for readability. Included human figures show examples of the artistic style of each class: Northern Running Figures (NRF), Dynamic Figures (DF), Post-Dynamic Figures (PDF), Simple Figures with Boomerangs (SFWB), Simple Figures from Wilton River (SFWR), Round Headdress figures from Wilton River (RH).

3.5 Discussion

The accuracy attained by the networks tested demonstrate that this method presented can be used to separate previously identified stylistic classes of rock art without any prior training in the rock art domain. This demonstrates the capacity of transfer learning as a tool for further rock art analysis in the future. Of all the network architectures explored, AlexNet achieved the greatest classification accuracy on the rock art dataset in the one-shot setting. The ImageNet dataset served as the best background training data for all networks on which it was tested. This is a surprising result considering that the images in this dataset appear to be the least visually similar to the rock art data on which the networks were tested. This may be because the other datasets had fewer classes than ImageNet and may have caused the models to learn features that were too specific to be effectively transferred.

Most importantly, the method presented has the benefit of being less etic than existing observational or statistical approaches. While such an approach is by no means emic, the features of interest are extracted exclusively from data rather than being chosen by the researcher. For rock art analysis this means that any discriminating features that contributed to stylistic separation must be present and relevant within the rock art motifs and not independently identified by a researcher. This removes the bias inherent in manual feature selection. Analysis of the approach proves that learned features are sensitive to complex patterns that are not simply geometric but also stylistic. This is a key advantage over established statistical approaches such as Geometric Morphometrics which rely exclusively on geometric features distinguishing art forms and the correct identification of such features. The only disadvantage of the transfer learning approach over those that rely on hand-picked features is that this approach does not indicate precisely what it is that has been learned throughout the process. This contrasts with established statistical approaches which explicitly identify the nature of any patterns recognised (Travers and Ross 2016, 2017).

Researcher bias is further removed by the transfer learning approach whereby concepts of style and distance are learned from background data. This avoids the bias that would be introduced by defining rock art classes prior to training a machine learning approach on rock art data directly and disproves the contention of Dobrez and Dobrez (2019, p. 15) that ‘No appeal to Information Technology can override problems at the level of premises’. Without any fine tuning, the transfer learning approach was able to accurately make predictions about rock art style classes as inferred by Chaloupka (1984, 1993). By capturing clusters which distinctly correlate to established stylistic classes without being trained on this information directly strongly validates the choices of classes as distinct and separable styles. The ability to accurately separate these classes does not provide any further insight into the relationships between the styles each class represents. The analysis of the activation space does, however, clearly order these styles into a sequential gradient of similarity as shown in Figure 3.2. The dimensional reduction of the activation space has shown the order of stylistic similarity between classes matches the chronology originally developed by Chaloupka (1993) and further developed by Chippindale and Taçon (1998).

It should be noted that the styles identified through this approach are entangled with the class of images that are sampled within the data set. This is, in part, a limitation of the data set size, but more significantly a result of the observable trend in Arnhem Land art, which has only minor variation within a given class of art (such as human figures) for long time periods. This is particularly clear for the human class of figures where an identified stylistic phase is typically dominated by depictions of very specific technologies, postures, and activities. This is clearly demonstrated by the headdress depicted in motifs, which are distinct for each style yet have very limited variation within that style. In this way we can extrapolate that this method is only useful for distinguishing style within a specific class of artistic depiction (in this case human figures). This extends to suggest that if depictions of another class (such as macropods for example) from the same stylistic phases as represented by the human figures, it would be unlikely that they would be correctly associated with human figures of the same style. It is important to note that with traditional approaches to stylistic analysis the association of different classes of depictions belonging to the same style are heavily dependent on superimposition and only partly based on factors of artistic commonality such as brushwork (Chaloupka 1993; Chippindale and Taçon 1998; Lewis 1988). Where traditional approaches have identified such a commonality it is unclear if this observation is accurate or influenced by a knowledge of the motifs association to one another though the superimposition chronology. A detailed investigation of the activation space allows us to demonstrate that this method is still sensitive to subtle stylistic variations within a class and is not entirely focussed on macro features within each class (such as headdress).

The t-SNE dimensionality reduction technique proved effective for visualising the encoder's activation space so that learned style information could be viewed as a stylistic spectrum. Figure 3.2 shows that the AlexNet model trained on ImageNet data, which resulted in the highest accuracy of all tested model/ data combinations, was able to independently reproduce Chaloupka's chronology from learned features. This implies that the progression of artistic style over time occurred on a stylistic gradient with similar human depictions occurring at similar times. It follows that a gradual development of style rather than sudden and significant innovation may best explain the broad changes in art style in the Arnhem Plateau region. This stylistic gradient represents the temporal transition between styles apart from the Northern Running Figures. The position of the Northern Running Figures in the stylistic spectrum does not agree with their temporal position in the broad Arnhem chronology. This stylistic uniqueness may be indicative of the geographic isolation of this style, with its limited distribution to the northwest corner of the plateau. The development of this style could be interpreted to have occurred in a way that was less influenced by art of previous times and is similarly less influential on future stylistic evolution of the region. An artistic isolation that matches the limited geographic distribution of this style would be difficult or impossible to infer via other methods.

A similar uniqueness can be observed in the rock art data from the Wilton River Region. Two classes were selected from this region that represented art that matched Chaloupka's Simple Figures class and those that distinguished themselves with distinct round headdress. The Simple Figures from the Wilton River Region closely related to Chaloupka's complex of Simple Figures, however, they were still distinctly separable. This is also true for those with the distinct round headdress which occur on the outermost extreme of the stylistic gradient observed in the network's activation space. This may show regional uniqueness developing later in the chronology. The Wilton River can be interpreted to be more closely related to the wider Arnhem Plateau styles during the Post-Dynamic Figures phase as the Post-Dynamic Figures class was only populated with art from Wilton River and fits appropriately in the chronology. During the later Simple Figure phase of rock art production in Arnhem Land, the Wilton River motifs may have become more regionally distinct. These distinctions still fall into the larger Simple Figures stylistic category but can also be further distinguished through classification. This provides a means by which nuanced differences in stylistic changes can be detected, quantified and given a relativistic account of their presence in a broader spectrum. The observation of nuanced stylistic differences and their attribution to a geographic trend, a temporal stylistic locality or the individualistic expression of distinct artists has been raised in the literature without a well-established means by which to determine these differences (Johnston 2017).

The placement of style on a continuous spectrum organised by comparative stylistic distances, allows class definitions to be made with a mathematical basis. This not only removes the subjectivity of class definitions but also allows individual data points to be viewed in a local neighbourhood of stylistic similarity, its placement therein possibly indicating more nuanced relationships to its localised peers. It may be possible to gain insight into what distinguishing features the neural network has learned through inspection of the individual figures represented by each point in Figure 3.2. Similar features can be seen within individual classes as well as between adjacent classes. The Dynamic Figures can be seen to be largely clustered together with a gradation of features being present. The class cluster shows figures with bolder outstretched running legs with a greater degree of infill being plotted closer to or overlapping Northern Running Figures. Figures with detailed grass skirts and other adornments are also plotted closely together. One outlier plots closely to the Simple Figures with Boomerangs class. This outlier has a more upwards posture and simple line work than other Dynamic Figures and these features may indicate their alignment with the Simple Figures with Boomerangs class.

Post-Dynamic Figures are mostly plotted in a cluster that is close to Dynamic Figures with the exception of four outliers which plot closer to the Simple Figures recorded in the Wilton River Region. This may be indicating that the Post-Dynamic Figure images used were all recorded in the Wilton River Region. These four outliers may demonstrate some geographic rationalisation to the Wilton River area within the Post-Dynamic Figures class.

One notable outlier to the Simple Figures class is a figure with a grass skirt. This figure was plotted among the Dynamic Figures class closely fitting with the only other examples within this data set depicting grass skirts. This makes the characterisation by the neural network obvious for this figure.

Interpretations of the images that make up the stylistic gradient are limited by the data size for each class and inferences from visual inspection must be considered loosely. The outliers and separation of clusters within the limited data size may indicate individual artistic expression (Johnston 2017). However, the broad pattern and transitions between the styles are made clear and some significant indication of what features the machine may have considered can be clearly observed. This adds value to the approach as it allows some amount of interrogation of the results which could be further strengthened with the inclusion of more data. Finally, the success of this case study suggests a much wider use for machine learning approaches within archaeological research. The transfer learning methodology means that the training data set is generic and so can be applied to any archaeological assemblage, including those in 3D and colour. It removes the need to use large, research question specific, training data and so opens this method for use on other material culture items such as pottery and stone artefacts.

3.6 Conclusion

This research demonstrates that machine learning provides a means by which minor stylistic patterns in rock art can be detected, quantified and analysed. Knowledge of other associated variables such as geographic distribution allows some elements of the unsupervised stylistic distinctions to be better understood. This suggests a considerable potential role for this approach in resolving chronological and stylistic questions in rock art research more generally. The application of transfer learning has been able to identify a new Arnhem Land rock art style. This method has demonstrated that Simple Figures from Wilton River are categorised separately to other early anthropomorphic figurative art styles in Arnhem Land. This way of organising style demonstrates the philosophical concept of styles existence as identification via comparison (Wiessner 1984). Organisation of style in such a continuum may remove the subjectivity of stylistic class definition and provide universal means by which style can be organised in a cultural context, for almost any archaeological materials.

3.7 Acknowledgements

The language, images and information contained in this publication includes reference to Indigenous Knowledge including traditional knowledge, traditional cultural expression and references to biological resources (plants and animals) of the Marrku and Dakkal people. The source Indigenous Knowledge is Confidential Information, traditional law and custom applies to it and the Marrku and Dakkal people assert copyright over it in addition to any copyright in the complete work. The language, images and information are published with the consent of Mimal Aboriginal Corporation

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3.8 Data availability statement

The source code for the rock art transfer learning is available at https://github.com/keeeal/rock-art-transfer-learning.

CHAPTER FOUR

Chapter 4: Reconstructing archaeological palaeolandscapes using geophysical and geomatic survey techniques: An example from Red Lily Lagoon, Arnhem Land, Australia

Jarrad Kowlessar[1], Ian Moffat[1], Daryl Wesley[1], Mark Willis[2,1], Shay Wrigglesworth[3,4], Tristen Jones[5], Alfred Nayinggul[3] and the Njanjma Rangers

1. Archaeology, College of Humanities, Arts and Social Sciences, Flinders University
2. Sacred Sites Research
3. Njanjma Rangers
4. Kakadu National Park
5. Department of Archaeology, The University of Sydney

An earlier version of this chapter is under review for publication in Plos One.

Approximate contribution of co-authors: Jarrad Kowlessar (65%), Ian Moffat (5%), Daryl Wesley (5%), Mark Willis (5%), Shay Wrigglesworth (5%), Tristen Jones (5%), Alfred Nayinggul (5%) and the Njanjma Rangers (5%).

4.1 Abstract

Arnhem Land is a key region for understanding the Pleistocene colonisation of Australia, due to the presence of the oldest sites in the continent. Despite this, conventional archaeological survey has not been effective at locating additional pre-Holocene sites in the region due to a complex distribution of geomorphic units caused by sea level rise and coastal aggradation. This research uses geophysical and geomatic techniques to map the subsurface distribution of the geomorphic units in the Red Lily Lagoon region in eastern Arnhem Land. This reveals a complex Pleistocene landscape, which offers the potential to locate additional archaeological sites and so reveal more about the lifeways of the earliest Australians.

4.2 Introduction

Archaeological attention is often focused on occupation sites, yet in the context of palaeolandscapes that are no longer visible in the surface morphology, archaeological understanding of these records is significantly limited. This is especially challenging in the long-lived cultural landscapes of Australia's north coast, which have undergone significant palaeogeographic change during human occupation.

The detailed reconstruction of past landscapes facilitates effective predictive modelling of archaeological site location and allows archaeological sites to be placed in their physiographic and environmental context. Environmental context provides an important means to interpret the presence and provenance of cultural material.

Geophysical techniques provide a non-invasive, time- and cost-effective means of investigating the subsurface (Cozzolino et al. 2018; Seidel and Lange 2007) and are widely used for archaeological and geological investigations (Bottari et al. 2017; Diallo et al. 2019; Niculiţă et al. 2020; Oliveira et al. 2019; Papadopoulos 2019; Simyrdanis et al. 2018). Electrical Resistivity Tomography (ERT) is a geophysical technique that measures the resistance of a volume of the subsurface by transmitting electrical current between electrodes (Cozzolino et al. 2018; Seidel and Lange 2007: 208–212). The depth of each measurement is controlled by the electrode spacing, and multiple measurements with different electrode spacings are combined to construct a 2D profile or 3D data volume. A mathematical modelling procedure called inversion is used to estimate the conditions that best reflect the measurements obtained, and so produce a profile of resistivity that can be interpreted for geological features which can inform models of palaeolandscapes (Loke and Barker 1995).

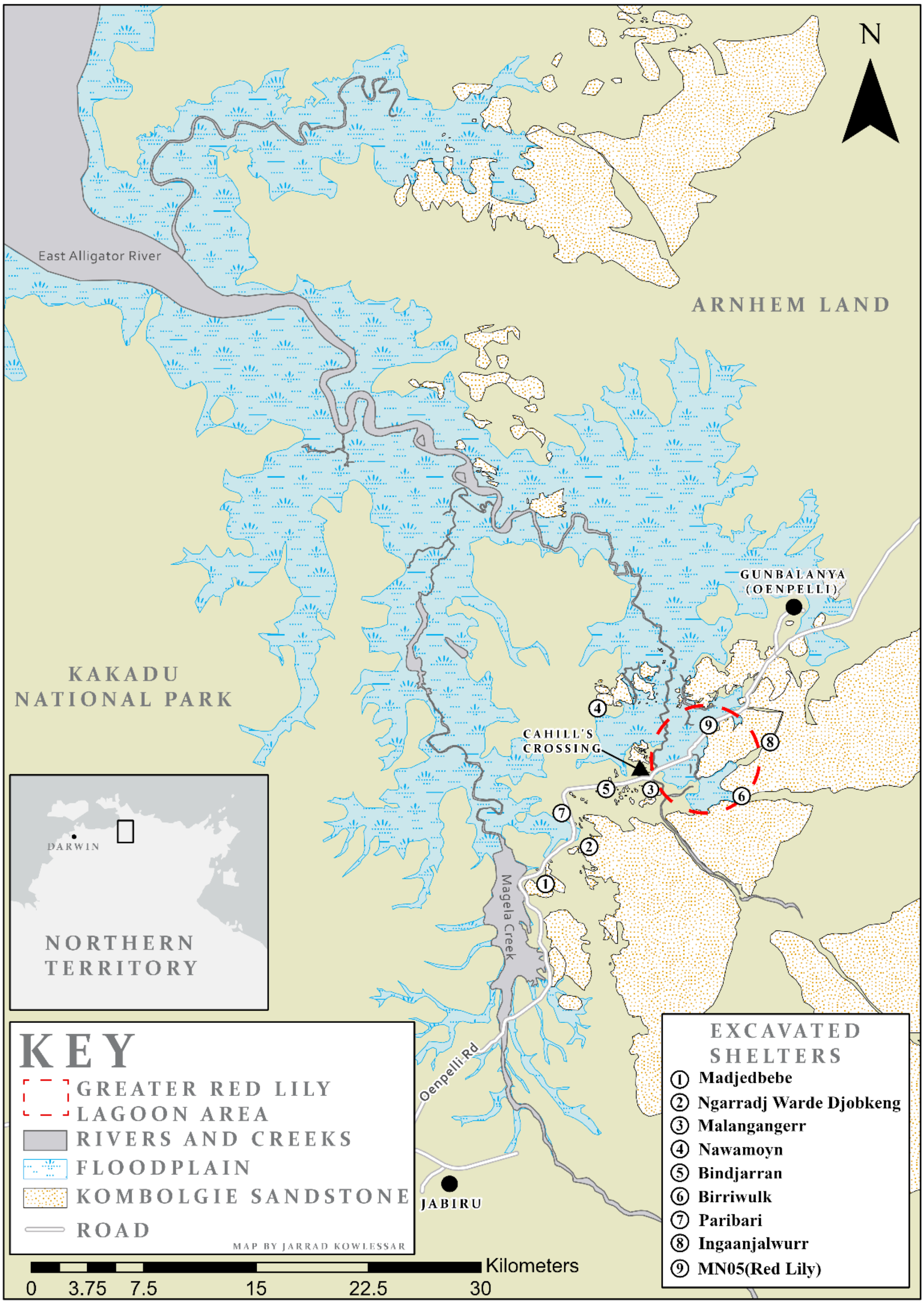
Modern geomatic approaches allow geophysical data to be combined with detailed surface, and elevation modelling. Combining surface and subsurface models allows a detailed interpretation of palaeogeographic changes and even the estimation of past land surface models creating detailed models of palaeolandscapes.

The Greater Red Lily Lagoon Area (GRLLA) (Figure 4.1) is a province of exceptional archaeological significance in Arnhem Land, northern Australia. It is situated at one of the easternmost extents of the East Alligator River floodplain, where the modern river and abandoned palaeochannels are adjacent to the sandstone escarpment of the Arnhem Plateau geological formation. This significant boundary between the low lying floodplains and the sandstone highlands of the Arnhem Plateau have been occupied by humans for over 60,000 years (Clarkson et al. 2017) and is the site of countless significant archaeological sites including some of the most iconic rock art panels in Australia (Brandl 1973; Chaloupka 1993; Chippindale and Taçon 1993; Jones et al. 2017a; Jones et al. 2017b; Lewis 1988; Mountford 1950, 1956, 1964, 1965, 1967, 1975; Wesley et al. 2017). This is a key landscape for understanding the early human occupation of Australia, with four sites greater than 20 ka having been found within 15 km of the GRLLA (Allen and Barton 1989: 102; Clarkson et al. 2017; 2015; Schrire 1982: 75, 110–145).

Interpretation of the art and material culture of Indigenous people in this area can be enhanced by developing a better understanding of the past landscapes and their relationship to the locations of human activity. The people living in the GRLLA have seen a significant environmental boundary affected by the climate changes of the last glacial cycle. Over the period of human occupation in this region, the landscape has been subject to dramatic environmental change, transitioning from a semi-arid location more than 350 km from the coast during Marine Isotope Stage 3 (MIS 3) to becoming a coastal mangrove swamp at the Holocene sea level highstand and then a seasonally inundated floodplain more than 40 km from the coast today (Allen and Barton 1989; Taçon and Brockwell 1995; Woodroffe 1988). These environmental changes are broadly mirrored in the subjects and chronology of the rock art in the area, presenting an Indigenous vision of this landscape and its environmental changes (Chaloupka 1993). Similarly, excavated cultural materials from occupation sites in the East Alligator River area have provided important insights about human activity over the last 60,000 years and many behavioural adaptations to these changing environments over this time (Allen and Barton 1989; Clarkson et al. 2017; 2015; Jones 1985; Roberts et al. 1990; Schrire 1982; Shine et al. 2016; 2015; 2013; Wesley et al. 2017; Woo 2020).

A key interest for researchers in Arnhem Land is locating additional Pleistocene cultural deposits, such as those located at Madjedbebe (Clarkson et al. 2017). While many of the early excavations in the region located sites with pre-Last Glacial Maximum (LGM) ages (Allen and Barton 1989; Jones 1985; Kamminga and Allen 1973; Schrire 1982), subsequent research has mainly yielded sites with Holocene chronologies (Shine et al. 2015; 2013; Wesley et al. 2017). While sites of any age provide important information about the rich human history of the region, the location of new sites of Pleistocene age will facilitate the testing of hypotheses regarding the stratigraphic integrity of previous dating results (Smith et al. 2021; Smith et al. 2019b; Williams 2019; Williams et al. 2021a; 2021b) and provide further information about pre-Holocene life histories. Further, all Pleistocene sites excavated in this region have been rock shelters and so provide a selective understanding of the life history of the people who occupied this landscape. We contend that the inability of recent excavations to replicate the antiquity of Madjebebe is based on the geomorphology of the excavation locations chosen rather than the presence of suitable sites in the region, which can be addressed by developing a more detailed model for landscape evolution.

Whilst the broad environmental history of the region over the period from the LGM to today has been characterised for the South Alligator River and Magela Creek floodplains (Wasson 1992; Woodroffe 1988; Woodroffe 1993), the subsurface geomorphology of the floodplain east of the East Alligator River is yet to be investigated. In order to address this research gap, mapping of the sedimentary facies and bedrock geomorphology of the GRLLA using the non-invasive geophysical method of Electrical Resistivity Tomography (ERT) has been undertaken. The results were used to analyse the distribution of rock art sites with reference to the palaeolandscape of the region and to model where new archaeological sites of Pleistocene age may be located. This work showcases the importance of accurate models of past landscapes through a detailed study of the culturally important Red Lily Lagoon section of the East Alligator River floodplain.



SOURCES: ESRI, GARMIN, FAO, NOAA, USGS

Figure 4.1 East Alligator River floodplain and the Arnhem Plateau.

4.2.1 Environmental Background

North Australian Climate History

Northern Australia has experienced wet-dry seasonality and monsoon events since before 150 ka, the seasonality and severity of these events were affected by global climate patterns (Beaufort et al. 2010). During MSI 3 and before the transition into the LGM, the region had a humid but cooler climate than present day (Reeves et al. 2013a; Samuel et al. 2021; Van der Kaars and De Deckker 2002; Wallis 2001). This period saw high fluvial activity across the continent (Nanson et al. 2008; Reeves et al. 2013a; Veth et al. 2009). This has been demonstrated for areas around East Alligator River with palaeochannels dating to this time showing multiple cycles of incision and infilling (Nanson et al. 1993).

During MIS 3, Australia was wettest between 49 and 40 ka (Kemp et al. 2019) before becoming increasingly dry leading up to and during MIS 2 (29–14 ka) (Reeves et al. 2013b; Samuel et al. 2021). The increasing dryness was also reflected in monsoon events that were less severe than those of the modern day (Reeves et al. 2013b; Samuel et al. 2021).

This LGM period saw dramatic changes to the global sea level and temperature as ice caps increased to their maximum extent. This had profound effects on the climate of northern Australia. During the LGM, sea level was at least 120 m lower in northern Australia (Larcombe et al. 1995), which exposed large areas of the continental shelf and opened land bridges on the Sahul Shelf between New Guinea and Australia. Exposing this land bridge resulted in major changes to the ocean circulation that greatly restricted the warm shallow waters that feed the tropical rainfall in the region (Reeves et al. 2013a; 2013b). This caused a drier period in Northern Australia. The dramatically different base level also had significant impacts on the geomorphology of fluvial systems in the region.

MIS 2 contrasts with the wet tropical climate that preceded in MIS 3 as well as the contemporary tropical climate which followed during MIS 1. It was terminated by a warming event that coincided with sea level rise and flooding of the Sunda shelf (Reeves et al. 2013a; 2013b). This flooding of the Sunda Shelf along with the deglacial warming in the region led to the return of the seasonal monsoon which characterises the contemporary climate of northern Australia (Reeves et al. 2013b).

West Arnhem Land Geology and Geomorphology

The GRLLA study area is located at the boundary between the Archean to Paleoproterozoic Pine Creek Orogen and the Palaeo-Mesoproterozoic McArthur Basin geological provinces, which correspond with the distribution of the Arnhem Land floodplains and plateau (respectively). The

Paleoproterozoic Kombolgie Formation dominates outcrops in the Arnhem Land Plateau (see Figure 4.7). This formation is made up of fluvial sandstones as well as some extrusive volcanic units. The sandstones of the Kombolgie Formation are a ferruginous fine- to coarse-grained quartz arenite. There are four distinct sandstone lithologies within the Kombolgie Formation: Marlgowa, Gumarrirnbang, Mamadawerre and McKay Sandstones which are differentiated principally by quartz grain size (Ahmad et al. 2013; Nott and Roberts 1996; Ojakangas 1979).

The Kombolgie Formation of the McArthur Basin unconformably overlies the Pine Creek Orogen units, which extend westward. The Pine Creek Orogen is made up of sedimentary and volcanic rocks which have undergone metamorphism and deformation and then deep weathering through laterization. This laterized surface is known as the Koolpinyah surface, which forms broad undulating lowlands that reach the coast and continue as far west as Darwin (Figure 4.1). The Koolpinyah surface underlies the coastal alluvium of the floodplains of the Alligator rivers. Discrete outcrops of Archean basement inliers are also present locally in the floodplain (Ahmad et al. 2013; Ahmad and Hollis 2013; Nott and Roberts 1996; Ojakangas 1979).

The denudation rate of the Koolpinyah surface has been shown to be up to eight times higher than that of the Kombolgie Formation sandstone of the Arnhem Plateau. Denudation rates of these two surfaces have been shown to be related to the climate events of the glacial cycles of the past 500 ky (Nott and Roberts 1996). The two major drivers of denudation are cycles of valley incision during sea level lowstand and valley infilling during highstands, along with increased fluvial activity associated with dry/wet climate transitions of the glacial cycles (Nott and Roberts 1996: 886–887). With its much lower denudation rates, the Kombolgie sandstone forms a barrier to the marine incursions that have occurred repeatedly over the Quaternary period. The difference in denudation rates between the two land surfaces increases their relief relative to one another (Nott and Roberts 1996). The floodplains of the Alligator rivers are formed in the low-lying valleys of the Koolpinyah surface. These lowlands contain meandering, tidally impacted fluvial systems that have accumulated sediments eroded from the Kombolgie and Koolpinyah land surfaces. In this way, the low-lying valleys of the floodplains act in contrast to the eroding uplands of the Koolpinyah surface and are gradually increasing in elevation as sediments collect there.

At the edges of the sandstone escarpments, colluvial sands created by the eroding sandstone collect as slope aprons at the foot of the escarpments and as alluvial fans that fill valleys throughout the Arnhem Plateau (Nott and Roberts 1996). Some of these sediments are mobile enough to reach the floodplains. The sand component of floodplain sediments comes from the erosion of the Kombolgie Formation whilst silt, clay and terrigenous solutes come from the erosion of the Koolpinyah surface (Nott and Roberts 1996; Wasson 1992; Woodroffe 1993). Figure 4.2 demonstrates the relationships between the Kombolgie sandstone escarpment, the Koolpinyah surface and the floodplains of the East Alligator River.

The lower-lying areas of the Koolpinyah surface, which are currently floodplains of the Alligator rivers, followed similar wide flat valley forms before the sea level rise at the end of the LGM but were less elevated (Nanson et al. 1993; Wasson 1992; Woodroffe 1993; Woodroffe et al. 1986). These alluvial valleys are characterised by unconsolidated sediment unconformably overlaying bedrock (Dalrymple et al. 1992: 1141), in this case the Pine Creek Orogen conglomerate capped by the laterized Koolpinyah surface (Wasson 1992; Woodroffe 1993; Woodroffe et al. 1986).

The sedimentary record of Megela creek demonstrates that the Alligator rivers region was a fluvial landscape for the entirety of the Quaternary period (Nanson et al. 1993). Fluvial activity has been heavily influenced by the glacial cycles over this period. The Quaternary has demonstrated cycles of channel incision (during glacial low stands) and infilling (during deglacial transgressions). Fluvial activity has also been impacted by the climatic (changes in precipitation) and eustatic (and associated base level) changes of the glacial cycles. This process has left the valley weakly incised in the Koolpinyah surface, as a result of channel incision during periods of lowered base level (Nanson et al. 1993). Older sediments remain in terraces along the valley edges but the sediments in the central parts of the valleys are generally reworked by recent fluvial activity. The most recent palaeochannels were formed during the last glacial cycle.

The sea level transgression following the LGM flooded the valleys below the Arnhem Land escarpment. This flooding occurred between 8 and 6 ka in the South Alligator River valley and is thought to be similarly timed in the East Alligator River valley (Nanson et al. 1993; Woodroffe 1993: 261; Woodroffe et al. 1986: 19). The transgressive flooding first reached Magela Creek around 7.7 ka and continued until between 5.5 and 7 ka (Wasson 1992: 90).

Alligator Rivers Morphology

The contemporary South and East Alligator rivers are typical tide-dominated estuaries with a funnel-shaped geometry where they enter the ocean and alternating straight and meandering sections moving landward (Dalrymple et al. 1992). This morphology is a result of interacting marine and fluvial forces within the estuary (Dalrymple et al. 1992). The tidal limit of the East Alligator River estuary occurs a short distance into the sandstone plateau, where elevation increases from the flat floodplain valley floor (Saynor and Erskine 2013). Fluvial energy (river currents) decreases seaward. In the middle section of a tide-dominated estuary, fluvial and tidal currents meet with roughly equal energy, and the river tends to meander. The mixed-energy zone is the lowest-energy zone in the estuary and therefore is the site of the deposition of finest-grained sediments from both marine and fluvial sediment loads, with grain size increasing both seawards and landwards from this central section

(Dalrymple et al. 1992: 1134–1136). The sinuosity (meandering form) of the river in these low-energy zones is thought to be caused by frictional energy gradients forming point bars on small curvatures in the channel path. The gradient of depth across the channel creates a pressure gradient in the current which curves the water with increasing force around the bends of these point bars cutting into the outside shoulder of the channel. Sinuosity will develop into these distinct meandering sections where the mixed-energy zone of the tide-dominated estuary occurs in a section of the river valley where the channel is unconfined (Dalrymple et al. 1992: 1136).

The landward straight section which is upstream of this mixed-energy zone is dominated by fluvial river currents, and the seaward straight section is dominated by marine tidal currents (Dalrymple et al. 1992: 1134–1136; Woodroffe et al. 1986: 28–32).The straight-meandering-straight, tidally dominated estuary morphology can only develop with a relatively stable sea level as the mixed-energy zone needs to be stable in location for some time before the physical forces (tidal and fluvial currents) can form this morphology. During the transgressive phase of sea level change, this zone will move rapidly and cause less morphological changes as estuaries are formed from the existing fluvial system and land surface configuration (Dalrymple et al. 1992: 1140; Woodroffe et al. 1989). The morphological changes brought about by the three distinct energy zones associated with tide-dominated estuaries will occur once sea level is stable or once the rate of sediment supply exceeds the rate of relative sea level change and infilling of the estuaries occurs (Dalrymple et al. 1992: 1140; Woodroffe et al. 1989). The three energy zones will gradually migrate seaward as the coastline (and zone of tidal influence) progrades.

This estuary morphology has been further characterised in the case of the much more intensively studied South Alligator River, providing an analogue of the morphology of the East Alligator River (Saynor and Erskine 2013; Woodroffe et al. 1989: 755). Along the South Alligator River, the following channel forms have been identified, listed in order moving landward: estuarine funnel (river mouth and deltaic shelf), sinuous meandering segment (mixed-energy zone), cuspate meandering segment and the upstream tidal channel (Woodroffe et al. 1989: 740–741; Woodroffe et al. 1986). Figure 4.7 demonstrates these channel forms in the contemporary East Alligator River.

The cuspate meandering and upstream sections of the tidal channel together form the fluvially dominated landward straight section of the South Alligator River estuary (Dalrymple et al. 1992; Woodroffe et al. 1986: 43–45). The cuspate meanders have the form of pointed inside river bends with wide reaches. Mid-channel shoals are usually present between these pointed cusps. These sections form in areas of past meanders where the mixed-energy zone has moved seaward due to progradation and now the channel is fluvially dominated. Increasing the energy and reducing the sediment deposition in the meandering zone causes channel bank erosion following the sharp pressure gradient of the original meander's point bar, widening the channel at this bend and cutting the point bar to create the mid channel shoal (Dalrymple et al. 1992; Woodroffe et al. 1989: 741,755). The upstream tidal channel describes the segment of the estuary with the greatest fluvial influence, which extends from the cuspate section to the tidal limit. This section has meanders with sharp bends and long straight reaches (Woodroffe et al. 1989: 741; Woodroffe et al. 1986).

Driven by sea level change following the LGM, the South Alligator River region went through a developmental sequence, described by four major phases: Transgressive phase, Big Swamp phase, Sinuous phase and Cuspate phase.

The Transgressive phase is described as the period of post glacial sea level rise which transgressed the contemporary areas of the South Alligator River between 8 and 6.8 ka (Woodroffe et al. 1989: 735). A number of models for this transgression have been put forward with the favoured model describing a rapid transgressive flooding occurring over almost the entire extent of the modern floodplains (Woodroffe et al. 1989: 117–119). This model has been supported by the presence of mangrove materials in palaeochannels of the South Alligator River dating to between 6.8 and 5.3 ka. Sea level rise ceased around between 6.5 and 6 ka in this area when present day sea level was reached (Woodroffe et al. 1986: 127).

The Big Swamp phase is described as a period following marine transgression and the establishment of estuaries by 6.8 ka, when mangroves flourished across the South Alligator River region (Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985). Mangrove sediments dating to this period have been uncovered across nearly the entire floodplains of the South Alligator River. With sea level stabilisation and the sedimentation of estuaries increasing due to mangrove development, the movement of marine water began to be restricted and reduced, and the mangrove habitat receded (Woodroffe et al. 1989). Whilst the development of mangroves has been suggested to have been a rapid and far-reaching process (Woodroffe et al. 1986) the decline of the mangroves has been characterised as more complex and locally variable across the Alligator rivers (Wasson 1992; Woo 2020). The sedimentation of individual channels may have produced poor drainage and hypersaline mudflats which cause rapid localised mangrove decline.

The Sinuous phase is described as a period of river channel migration through the far-reaching mangrove sediments deposited through the Big Swamp phase. This phase has left remnants of past meanders as oxbow lakes along the length of the South Alligator river showing the locations of past mixed energy zones throughout the history of progradation.

The Cuspate phase is described for its distinct channel morphology of eroded riverbanks, and sharp pointed cusps in river bends. As the energy zones prograded seawards, the previous low energy meander sections began to enter the higher fluvial energy zone and bank erosion morphed the channel in these sections into cuspate forms beginning around 2.5 ka (Dalrymple et al. 1992; Woodroffe et al. 1989: 735,741,755).

The morphology of the plains in the river valley lowland of the South Alligator River region also changed over these distinct phases. During the LGM these areas were low laying valleys with fluvial sediments overlaying the bedrock. After the Transgressive phase, these valleys became deltaic-estuarine plains. Once these plains filled with mangroves during the Big Swamp phase sediment accretion levelled these regions into flat topography. During the Sinuous phase as mangroves declined, these regions became saline mudflats. The freshwater dominance of the monsoon climate especially during the cuspate phase caused seasonal flooding of the mudflats transforming them to the contemporary freshwater floodplains. These freshwater floodplains are populated by grasslands as well as open melaleuca paperbark forests and areas of semi-permanent standing water near the valley edges termed ‘back water swamps’ (Wasson 1992; Woodroffe et al. 1989).

Sedimentary Facies and Stratigraphy

The stratigraphy of the floodplains of the South Alligator River and Magela Creek have been well characterised through coring, dating and pollen analysis (Wasson 1992; Woodroffe 1993). This coring was used to characterise the Transgressive, Big Swamp, Sinuous and Cuspate phases of the South Alligator River (and East Alligator River by extension). Table 1 shows the identified layers and their ages, depths and elevation, and Figure 4.3 shows the full elevation ranges observed in the Magela floodplain for each surface and denotes the range of the top of each layer's surface. Figure 4.2 shows the major depositional layers in their landscape context relative to the Kombolgie escarpment and the eroding upland Koolpinyah surface.

Bedrock and basal sediments

Wasson (Wasson 1992) identified the bedrock depth through the Magela Creek floodplain as between 7 m (~-1 m elevation Australian Height Datum [AHD]) and 29.3 m (~-24 m elevation AHD). Bedrock was found to increase in depth below the floodplain near the modern East Alligator River, with its deepest measured depth being on the north side of the river in the centre area of the floodplain valley.

Above the bedrock, a layer of basal sands and gravels with an approximate thickness of 4 m was identified. At this layer's shallowest point, the top surface of this strata was sampled at a depth of 5 m (~0.5 m elevation AHD) (Wasson 1992: 124). At its deepest point sampled in the Magela floodplain, the top surface of this layer was found at a depth of 27.4 m (~-22.4 m elevation AHD) and the bottom of the layer was at a depth of 29.3 m laying unconformably on the bedrock (Wasson 1992: 28).

The basal sediment layer identified above the bedrock in the floodplains of the South Alligator River is comprised of gravels, quartz sands and weathered clays; these sediments are interpreted as pre-Holocene surfaces (Woodroffe 1993; Woodroffe et al. 1989: 743; Woodroffe et al. 1986; Woodroffe et al. 1985).

Freshwater fluvial and colluvial sediments

Above the basal sands and gravels in Magela Creek is a layer of sands and clays that have been characterised as fluvial sediments deposited in a system with no marine influence (Wasson 1992: 29). These sediments are interpreted to represent the land surface prior to the marine transgression and therefore have a Pleistocene to early Holocene minimum age (Wasson 1992: 90). These sediments formed fluvial terraces that were buried by younger sediments (Wasson 1992: 29). The top surface of this layer of pre-transgression fluvial sands and clay was found at a depth of 2.5 m (3 m elevation AHD) at the shallowest point sampled (Wasson 1992: 124) and a depth of 11 m (-8 m elevation AHD) at the deepest point sampled (Wasson 1992: 135).

In the South Alligator River, the basal sediments include layers of clean white sands which are interpreted as early Holocene or Pleistocene alluvial or colluvial deposits (Woodroffe 1993; Woodroffe et al. 1989: 743; Woodroffe et al. 1986; Woodroffe et al. 1985). The principal control on the distribution of the sediments appears to be the topography of the bedrock surface (Wasson 1992: 29).

Mangrove mud

Overlying the fluvial sediments of the floodplains of South Alligator River and Magela Creek is a layer of ‘blue-grey’ soft clay mud (Wasson 1992: 55–56,141; Woodroffe et al. 1989). Palaeobotanic analysis of samples from both areas have confirmed this to be mangrove mud, rich with in situ mangrove stumps, macrofossils and pollen (Wasson 1992; Woodroffe et al. 1989). Within the South Alligator River region this layer has a base level between -12 and -10 m AHD. Along Magela Creek, the bottom of this layer was found at an elevation of -10 m AHD (at around 15 m depth) at its deepest and found all the way to 3.8 m AHD (approximately 8.5 m depth) further inland in the upstream end of the Magela floodplain (Wasson 1992). This layer has a thickness which varies between 4 and 14 m along Magela Creek (confined by the gradient of the bedrock depth) (Wasson 1992) and between 2 and 8 m in the South Alligator River region (Woodroffe et al. 1989).

The Transgressive phase occurred between 8 and 6.8 ka with the Big Swamp phase lasting from 6.8 to 5.3 ka (Woodroffe 1993). The transgression first reached Magela Creek around 7.7 ka as demonstrated by dated mangrove pollen at the base of the blue grey clay layer where the creek first branches from the East Alligator River (Wasson 1992: 90). Mangroves reached the upstream extents of Magela Creek by 4.4 ka (Wasson 1992: 55–56,141). The contemporary elevation extent of mangrove distribution is between 3.7 and -1.0 m from mean sea level (Woodroffe et al. 1986). This ecological range appears to have been consistent in the region since at least the LGM (Wasson 1992: 90).

Laminated channel sediments

Laminated lenses of bluish-grey silt and fine-grained sand have been identified in the subsurface adjacent to the modern South Alligator River channel. These have been argued to represent lateral accretion deposits associated with channel migration and associated outbuilding sediments on river point bars (Woodroffe et al. 1989: 743). These sediments have been dated between 5.1 and 2.9 ka in sections occurring between palaeochannels and the contemporary river channel.

Transitional sediments

The blue-grey clay is overlain by a considerably thinner layer of grey clay. This layer was argued to be related to a transition from the Big Swamp estuarine environment to the modern freshwater dominated seasonal wetland conditions (Wasson 1992: 29–30). This layer was not identified directly throughout the South Alligator River region. However, a layer of undifferentiated sediments was identified occurring at comparable depths and stratigraphic sequence (overlying blue-grey mangrove mud) (Woodroffe et al. 1989: 743).

Floodplain sediments

The surface layer of the Magela floodplain was described as ‘dark brown/black clay’. Rich in organic material, this layer does not display visible sedimentary structures and is likely to be formed by the deposition of floodplain sediments and the in situ breakdown of grasses and sedges (Wasson 1992: 31). This floodplain clay layer is approximately 0.5–1.5 m thick but is difficult to distinguish from underlying transitional sediments (Woodroffe et al. 1989: 743).

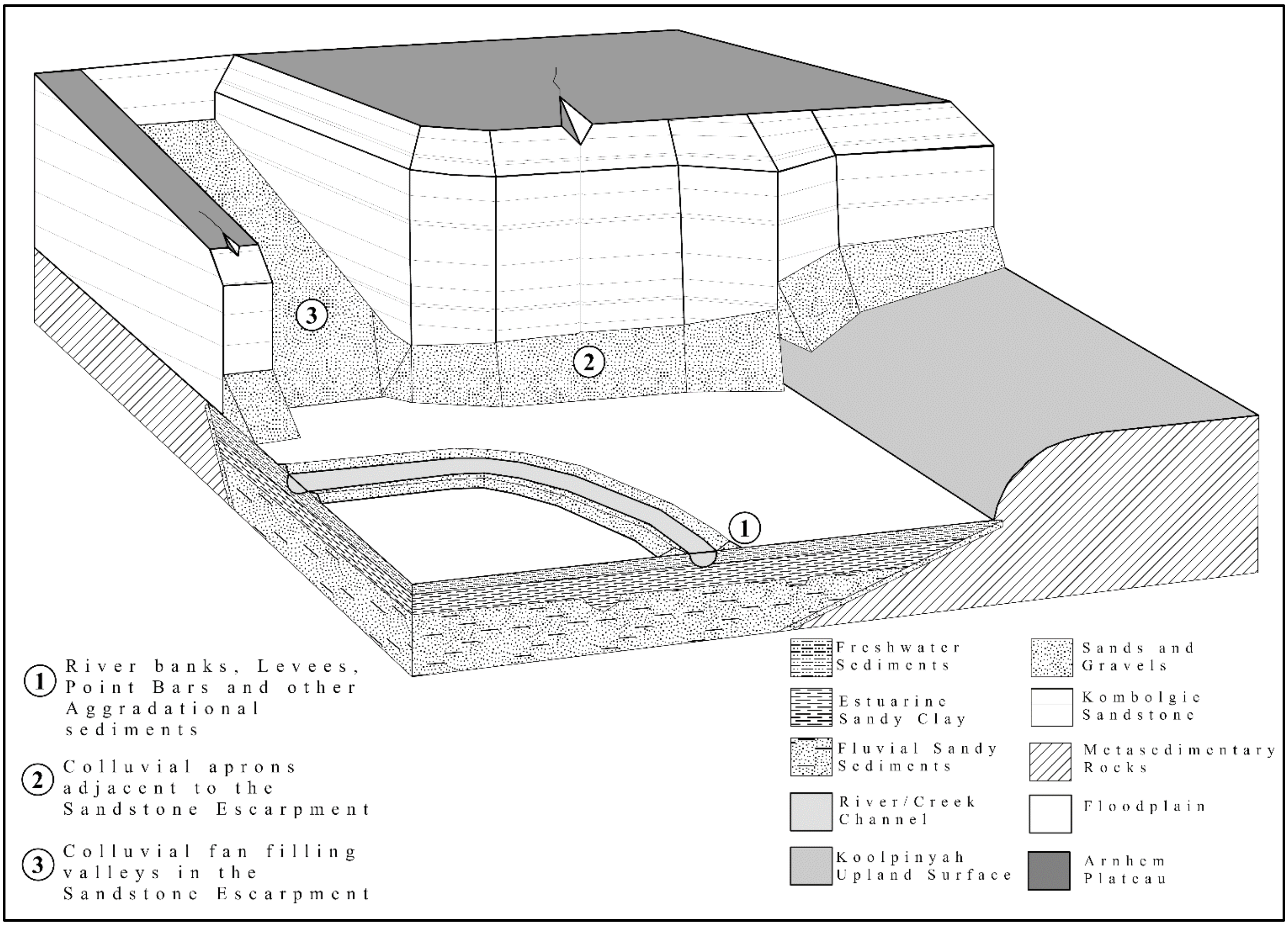


Figure 4.2 Key geomorphological features of the East Alligator River floodplain and Arnhem Plateau.

Table 4.1 Major depositional layers age, depth from surface and elevation of the top surface level of each of these layers as observed throughout the Magela Creek (Wasson 1992).

Depositional layers	Age	Depth to the top of the layer surface	Elevation (AHD) of the top of the layer surface
Bedrock	2020 to 1800 Ma	7 to 29.3 m	~-1 to -24 m
Basal sands and gravels	Unknown	5 to 27.4 m	~0.5 to -22.4 m
Pre-transgression land surface	>7.7 ka	2.5 to 11 m	3 to -8 m
Mangrove muds and clay	7.7 ka	~1.5 m	1.5 to 3.8 m
Freshwater floodplain clay	5 to1.7 ka	0 m	~3.5 to 5.5 m

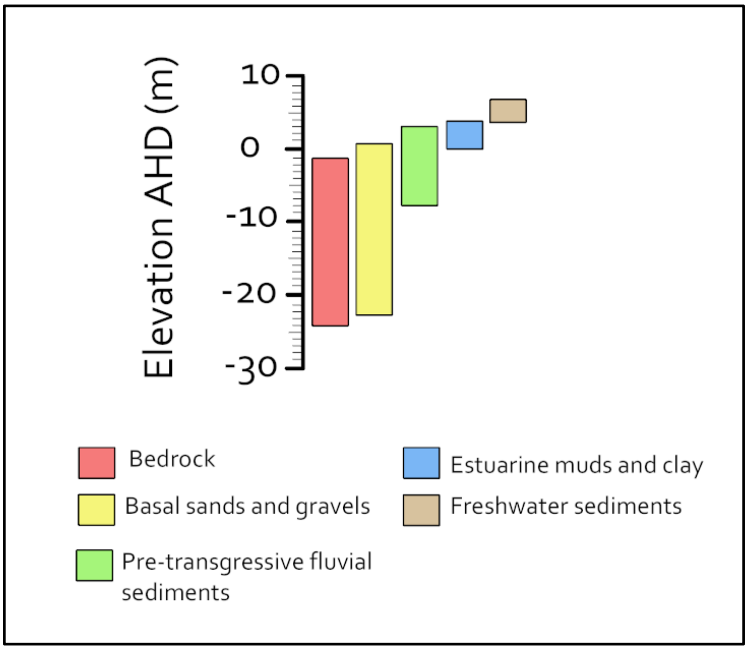


Figure 4.3 Elevation ranges as reported by Wasson (Wasson 1992) for each depositional layer of the Magela Creek floodplain.

4.2.2 Archaeology Background

Archaeology of the East Alligator River Catchment

Nine archaeological sites have been excavated around the estuarine portion of the East Alligator River catchment (Allen and Barton 1989; Clarkson et al. 2017; Clarkson et al. 2015; Jones 1985; Roberts et al. 1990; Schrire 1982; Shine et al. 2016; Shine et al. 2015; Shine et al. 2013; Wesley et al. 2017; Woo 2020). These sites account for the record of material culture of this area and are dominantly characterised by faunal remains (including shell and bone), stone artefacts and charcoal (Allen 1989; Clarkson et al. 2017; Clarkson et al. 2015; Jones 1985; Roberts et al. 1990; Schrire 1982; Shine et al. 2016; Shine et al. 2015; Shine et al. 2013; Wesley et al. 2017; Woo 2020). The locations of each shelter can be seen on Figure 4.1. All of these sites are sandstone rock shelters on the margins of the Kombolgie formation that overlook the East Alligator River or Magela Creek floodplains. These shelters are situated at different elevations, but all are located on colluvial aprons surrounding the sandstone margins. Table 2 describes each site's onset of occupation (based on dated material). These excavations, whilst limited in number, have significantly contributed to the discussion of human occupation of northern Australia over the last 65,000 years. This includes the late Pleistocene through to the modern period with particular detail for the mid-late Holocene following the marine transgression. This section will briefly review these material records and surrounding accounts of human activity.

Table 4.2 Excavations and derived occupation dates throughout the East Alligator floodplains region (Previously uncalibrated dates for Malangangerr, Nawamoyn and Paribari were calibrated using rCarbon with the SHCal20 calibration curve and reported with 1 sigma ranges).

Site	Source(s)	Maximum occupation*
Madjedbebe (Malakununja II)	(Clarkson et al. 2017; Clarkson et al. 2015; Jones 1985; Kamminga and Allen 1973; Roberts et al. 1990)	61 ± 10 ka
Ngarradj Warde Djobkeng	(Allen and Barton 1989: 102; Kamminga and Allen 1973: 29–36,64–66)	26,000 cal. BP

Malangangerr	(Schrire 1982: 75)	30,708–30,594 cal. BP
Nawamoyn	(Schrire 1982: 110–145)	26,034–25,256 cal. BP
Bindjarran	(Shine et al. 2015: 108)	13,140–12,771 cal. BP
Birriwulk	(Shine et al. 2013)	5290–4970 cal. BP
Paribari	(Schrire 1982: 45–74)	3,447–3,215 cal. BP
Ingaanjalwurr	(Shine et al. 2016)	1,900–1,300 cal. BP
MN05 (Red Lily)	(Wesley et al. 2017)	795–950 cal. BP

Pre-transgression (65,000 to 9000 years)

Madjedbebe (previously known as Malakununja II) has produced the earliest dated occupation for the region and Australia (Clarkson et al. 2017). The archaeology of Madjedbebe is characterised by an extensive stone artefact assemblage, faunal remains and shell middens. The site is situated in a sandstone rock shelter and sits on a colluvial apron at approximately 20 m elevation (AHD) adjacent to the Magela Creek floodplain (Clarkson et al. 2017: 306) at the northern edge of the sandstone escarpment. The site is elevated compared to the floodplain, which is ~3–4 m elevation (AHD). Aboriginal occupation at Madjedbebe has been dated from 65 ka and shows evidence of changing lithic technologies as well as ochre collection and grinding/processing of resources during this early time (Clarkson et al. 2017). Organic material preservation is largely limited to the Holocene. However, organic materials preserved from the early Transgressive phase can be used to infer some of the land use and subsistence practices during the early Holocene portion of the pre-Transgressive phase (see following section). Occupation during the pre-transgression has been recorded in Ngarradj Warde Djobkeng from 26 ka (Allen and Barton 1989: 102; Kamminga and Allen 1973: 29–36,64–66), Malangangerr from 24.8 ka (Schrire 1982: 75), Nawamoyn from 21.4 ka, (Schrire 1982: 110–145), and Bindjarran from 13–12 ka (Shine et al. 2015: 108).

Plant remains recovered from sediments of 65,000–53,000 years ago from Madjedbebe suggest an open forest and woodland and/or monsoon vine forest environment (Florin et al. 2020).

Transgressive phase (8.5-8 ka to 6.8 ka)

The Transgressive phase's period of occupation at Madjedbebe has abundant vertebrate remains demonstrating that small marsupials from grasslands, woodlands, and dry eucalypt woodland habitats were the primary food source during this period (Woo 2020: 197, 149–150). At the beginning of the transgression both estuarine and freshwater molluscan resources were a secondary source of food but as the mangroves became established towards the end of the Transgressive phase, resource harvesting of estuarine molluscs became dominant (Woo 2020: 198).

The earliest known material record of human interaction with the emerging East Alligator River environments of the Transgressive phase comes from dated shell midden contexts at Madjedbebe and Nawamoyn (Schrire 1982: 118; Woo 2020: 115,195). The shell assemblage from Nawamoyn broadly agrees with those from Madjedbebe but was less detailed in its recording and subsequent study (Schrire 1982; Woo 2020). The midden formation at both sites coincides with the earliest mangrove development for the East Alligator River valley around 7600 cal BP (Schrire 1982: 118; Wasson 1992; Woo 2020). The midden materials dated to the Transgressive phase show the presence of both freshwater and estuarine molluscs. Estuarine molluscs were more dominant within the midden and increased in exploitation over the Transgressive phase. Analysis of the shell of this period indicates that Madjedbebe was only used ephemerally during this time. Mollusc species present indicate that all areas of the developing mangrove forests were foraged during this phase whereas later periods saw only specific zones of the mangrove forest foraged (Woo 2020: 196). Woo (Chaloupka 1993) suggested that this broad mangrove foraging strategy was only possible owing to the early developmental stage of the mangrove habitats with a more open forest structure allowing greater accessibility. As these mangrove forests are established, the seaward zones of these forests became increasingly dense, thereby restricting access to the unique fauna of those zones (Hiscock 1999; Woo 2020: 196–197).

Florin et al. (2021) has investigated palaeoclimate for this region using the novel analysis of Pandanus nutshell (*Pandanus spiralis*) remains excavated from Madjedbebe. Variations within the $\delta^{13}C$ within this dated assemblage were used as a proxy for mean annual precipitation. These data suggested a period of increased precipitation between 9.7 and 7.1 ka which then steadily declined towards the modern day. Florin et al. (Florin et al. 2021) demonstrated the reliability of this approach using modern Pandanus nut shells collected across a transect with a significant precipitation gradient. The modern analysis demonstrated accurate predictions of precipitation in areas with well-drained soils. However, precipitation was overestimated in areas with standing water on the surface. Given the coincidental timing of the predicted increase in precipitation with the marine transgression in this region, the variation in $\delta^{13}C$ at Madjedbebe may be better explained by a change to the local hydrology related to the short distance from the site to the fresh/saltwater interface.

Additionally, analysis of grinding stones from Madjedbebe has shown that waterlily (*Nymphaea violacea*) was being processed at the site at 8320 cal BP (Hayes et al. 2021). This plant species grows in low-energy freshwater environments and was probably available locally in the East Alligator River due to increased sinuosity in this system due to the rapid increase in fluvial base level associated with the transgression.

Big Swamp phase (6.8 to 4-5 ka)

The Big Swamp phase at Madjedbebe coincides with a shift to estuarine mollusc foraging as the dominant food source, particularly those from the landward fringes of the mangrove forest (Allen and Barton 1989; Hiscock 1999; Woo 2020). The development of these extensive forests had considerable impacts on mobility, particularly in terms of restricting access to the seaward portions of mangrove habitat. Whilst these shifts in mangrove zone exploitation seem to be present in all excavated middens in the area, the timing of these shifts differ between sites (Woo 2020: 228). This is indicative that mangroves forest structure development was varied throughout the region, likely representing specific landscape transitions and subsequent forest development (Woo 2020: 228).

Foraging strategies were highly specialised and focused on molluscs by the peak of the mangrove development (Woo 2020: 228). Shell tools and scrapers appear in the site assemblages. This coincides with an observed decrease in lithic production in the area during this period (Schrire 1982: 250–251; Woo 2020: 225). Imported mollusc species have been observed among the assemblages at Ngarradj Warde Djobkeng, Nawamoyn, and Malangangerr. These species are all of coastal marine origin and therefore transported or traded to this site over significant distances (between 50–300 km) (Woo 2020: 225).

This period is also coincident with the appearance of bifacial points in many of the rock shelters in the region around 5–7 ka (Hiscock 1999: 98). It is unclear whether this occurrence is best timed with the Big Swamp or its subsequent decline but is likely to represent technology changes in the context of these major environmental changes (Hiscock 1999: 98).

During the Big Swamp phase the amount of *Pandanus spiralis*, an important food plant, within Madjebebe dramatically decreased (Florin et al. 2021 Fig. 2). This was attributed by the authors to decreased post-burial preservation, but we interpret this to reflect the relative unavailability of *Pandanus* in the region due to widespread mangroves and/or salt flats.

Sinuous phase (4 to 2 ka)

During the Sinuous phase as mangrove forests migrated seaward away from the escarpment region there is a reciprocal reduction in mollusc resource exploitation observed in middens in this area. The decline in shell foraging does not occur simultaneously or at the same rate at all sites along the East

Alligator River (Allen and Barton 1989: 102; Clarkson et al. 2017; Clarkson et al. 2015; Jones 1985; Kamminga and Allen 1973: 29–36,64–66; Roberts et al. 1990; Schrire 1982: 75,110–145; Shine et al. 2015: 108; Shine et al. 2013; Woo 2020). The rate of decline appears to be controlled by the sedimentation rates of the estuarine channels close to each site (Woo 2020).

This phase shows a peak of the new lithic technology production through many of the sites in the region including Nawanmoyn, Madjedbebe and Ngarradj Warde Djobkeng. This change in technology supports the argument that these tools are a risk management strategy in the context of the highly variable environments and associated resources of this time (Allen and Barton 1989; Hiscock 1999; Schrire 1982).

There is evidence of site abandonment or long occupation hiatus at many of the sandstone rock shelter sites in the areas around the upper reaches of the East Alligator River estuary (Allen and Barton 1989: 90–91; Brockwell et al. 2011; Hiscock 1999: 96–97). This has been argued to represent a population shift towards the more open occupation sites closer to the coast following mangrove loss (Woo 2020: 212). This response may have been driven by the development of salt flats over areas where mangroves were receding (Allen and Barton 1989: 90–91; Brockwell et al. 2011: 8; Hiscock 1999: 96). The timing of this site abandonment was synchronous with local mangrove decline. The timing of site abandonment/hiatus was different for each of the upper East Alligator River estuary sites with different abandonment times and rates observed for Madjedbebe and Ngarradj Warde Djobeng, likely reflecting mangrove decline patterns local to each site (Woo 2020). Reoccupation of the shelters local to the upstream sections of the East Alligator Estuary may not have occurred again until 1 ka (Allen and Barton 1989: 90–91; Brockwell et al. 2011; Hiscock 1999: 96–97). Birriwulk's sustained occupation first occurred during this time.

Cuspate phase (2 ka to present)

The Cuspate phase represents the most recent landscape usage, being the exploitation and occupation of the freshwater floodplains, which replaced the mangroves. A number of sites have evidence suggesting an increase in occupation during this time (Shine et al. 2016; Shine et al. 2013; Wesley et al. 2017). Ingaanjalwurr and MN005 also show evidence of occupation beginning during this phase. At MN05, which is located directly adjacent to Red Lily Lagoon, Wesley et al. (Wesley et al. 2017: 36) reached sandstone bedrock at a depth of 95 cm with basal sediments dating to 795–950 Cal BP. This shows an accumulation of 1 m of sandy sediment over around 1000 years (Wesley et al. 2017: 36). MN05 demonstrates a focus on freshwater species within the faunal remains with catfish (*Arius leptaspis)*, Barramundi (*Lates calcarifer),* freshwater turtle, and freshwater bivalve (*Mytilus sp.)* within the excavated assemblage (Wesley et al. 2017). Biriwulk showed the same focus on freshwater resources with the presences of catfish and freshwater turtle within excavation layers dated between 750 and 50 BP.

Analysis of grinding stones dating to ~690 cal BP from Madjebebe demonstrates that starch from *Cochlospermum fraseri* was being processed at the site (Hayes et al. 2021). This species is usually found in open eucalypt woodland.

Rock Art

There are a great number of painted rock surfaces throughout the East Alligator River area. The rock art has significant variation in the styles and depicts a diversity of subject matter (Chaloupka 1993). Rock art chronologies for Arnhem Land have been developed largely from the superimposition of relative sequences of motifs (younger paintings superimposed over the top of older paintings) (Chaloupka 1993). Direct dating has confirmed that some anthropomorphic styles are Pleistocene and others emerged in the Pleistocene-Holocene transition (Jones et al. 2017b). The overall rock art chronology, however, is aligned with the broader environmental changes within the landscape. This is evident through changes in subject matter such as large naturalistic macropods to the appearance of estuarine animal species such as fish and crocodiles (Chaloupka 1993). A proliferation of freshwater species such as fish and birds occur in the most recent styles of this region, and this reflects the most recent phases of environmental change with the extensive freshwater floodplains of the contemporary landscape (Chaloupka 1993).

4.2.3 Geophysical Investigation

ERT provides a geophysical method of modelling the subsurface using induced electrical current (Altmeyer et al. 2021; Martínez et al. 2009: 167). Current is induced and measured through electrodes partially inserted into the ground surface at a shallow depth (around 10-15cm). The arrangement of the current (injecting) and potential (measuring) electrodes is referred to as an array, and different array configurations will provide different samples of the subsurface resistivity. Typical array configurations include Wenner, Schlumberger and Dipole-Dipole (Dahlin and Zhou 2004). Wenner is a robust array that is less sensitive to noise from electromagnetic disturbance and subsurface heterogeneity (Cozzolino et al. 2018; Seidel and Lange 2007: 208–212). The Wenner array has a lower lateral resolution and will blur feature boundaries in this direction. The Schlumberger array is more sensitive to lateral boundaries and less sensitive to vertical changes (Seidel and Lange 2007: 208–212). The Dipole-dipole array is capable of deeper sounds from the same surface electrode coverage (per line measured). The Dipole-Dipole array is more sensitive to smaller features but also more sensitive to noise and disturbance from surface resistance heterogeneity (Seidel and Lange 2007: 208–212).

Visualising the continuous distribution of subsurface resistivity values of a profile in a meaningful way which can be interpreted in a meaningful way requires contouring of the data. This is the process of selecting discrete ranges of resistivity within the overall distribution and displaying these with a single unified colour (Cozzolino et al. 2018). The choice of resistivity values to be assigned to each group represented by a colour is important as one subsurface feature (such as a layer of sandy clay) may have a range of resistivity at different locations produced by changes in lithology, mineralogy, salinity and moisture (Chambers et al. 2012; Froese et al. 2005; Hsu et al. 2010; Maillet et al. 2005; Martínez et al. 2009; Matys Grygar et al. 2016). Effective geophysical interpretation of ERT inversion requires choosing resistivity display brackets that appropriately breaks colours into distinct groups that reflect the subsurface characteristics of interest and are not separated by changes that are beyond the resolution of our interest (such as local changes in moisture content or salinity within a single sedimentary layer).

ERT can characterise subsurface stratigraphy of fluvial systems including different depositional facies and the sediment-bedrock interface (Altmeyer et al. 2021; Martínez et al. 2009: 167). However, the facies identified are based on resistivity of the features and so aren’t informed by properties such as sedimentary structures or grain size, which can help inform stratigraphic interpretations using alternative methodologies (such as directly interpreting core samples) (Maillet et al. 2005; Matys Grygar et al. 2016). Thin or laterally confined stratigraphic units may also be below the resolution of ERT investigations (Matys Grygar et al. 2016).

ERT has great merit for the use in the East Alligator River floodplains. Following the geomorphological sequences that have been characterised for the floodplains of the South Alligator River and Magela Creek, the major depositional units that may be identified by this approach are bedrock (Kombolgie Sandstone or Koolpinyah Laterite), basal sands and gravels, fluvial sandy sediments (pre-transgression land surface), estuarine sandy clay (mangrove muds from the Big Swamp phase), and dominantly organic sediments (deposition from the Freshwater Floodplain environment) (Wasson 1992; Woodroffe 1993).

4.3 Methods

4.3.1 Landscape Modelling

The mapping of the contemporary land surface for the GRLLA study area was conducted using a Global Navigation Satellite System (GNSS) survey, drone-based photogrammetry and publicly available Light Detection and Ranging (LiDAR) data. Two digital elevation models (DEM) were used. The largest DEM was derived from LiDAR collected at 1 m resolution and resampled to 5 m resolution (Geoscience Australia 2018) that has a vertical accuracy of at least 0.30 m and horizontal accuracy of at least 0.80 m (Geoscience Australia 2018). The smallest DEM was derived from drone-base photogrammetry. A DJI Mavic 2 Pro drone was used to undertake aerial photography. An Emlid RS+ RTK GNSS link and a CHC X90+ static GNSS were used to georeference the data. ‘Structure from motion’ photogrammetry method was used to create the resulting DEM and orthophoto, which were processed using Agisoft Metashape software. The photogrammetry derived DEM had a spatial resolution of 26.4 cm This method is fully described in (Kowlessar et al. 2022a).

4.3.2 ERT Methods

Geophysical Field Survey

A geophysical investigation was conducted within the GRLLA study area in September 2019. September was chosen as this is the dry season of Northern Australia's yearly wet/dry tropical cycle and so has the least standing water across the floodplains. Four transects were chosen to sample the key landscape features that dominate the interface between the Kombolgie Sandstone escarpment and the directly adjacent East Alligator River floodplain. The features identified for geophysical survey are the floodplains, the incised valleys of the Kombolgie sandstone formation which run perpendicular to the floodplain, and the upland reaches of the sandstone valleys (See Figure 4.2 for examples of these features). Figure 4.4 shows the locations of the survey lines and Table 3 describes each line and their environmental and archaeological context.

Table 4.3 ERT line locations.

Line #	Length	Description	Environment and archaeology
1	982 m	Crosses the width of the floodplain from the sandstone escarpment.	Adjacent to a number of sites with extensive rock art inscriptions. Crosses over the visible palaeochannel of Red Lily Lagoon's remnant waterway.
2	314.52 m	Middle section of a valley through the stone plateau.	Forested with Melaleuca Paperbark trees. This valley is a major drainage path for this section of the escarpment. An extensive number of rock art sites overlook this valley.
3 (Section1)	627.26 m	Open section of a major valley that runs into the stone plateau from the floodplains.	Melaleuca Paperbark open woodland. The valley has a gentle slope descending towards the floodplain. Major rock art galleries surround this valley on all sides.
3 (Section 2)	953.67 m	Crosses the width of the floodplain from the escarpment valley to the northern escarpment edge.	Overlooked by several major rock art sites including a gallery with dated rock art panels (Jones et al. 2017b).
4	312.21 m	Crosses the width of the sandstone valley. Crossing Line 3 (Section 1) at a perpendicular angle.	Melaleuca Paperbark open woodland. The valley has a gentle slope descending towards the floodplain. Major rock art galleries surround this valley on all sides.

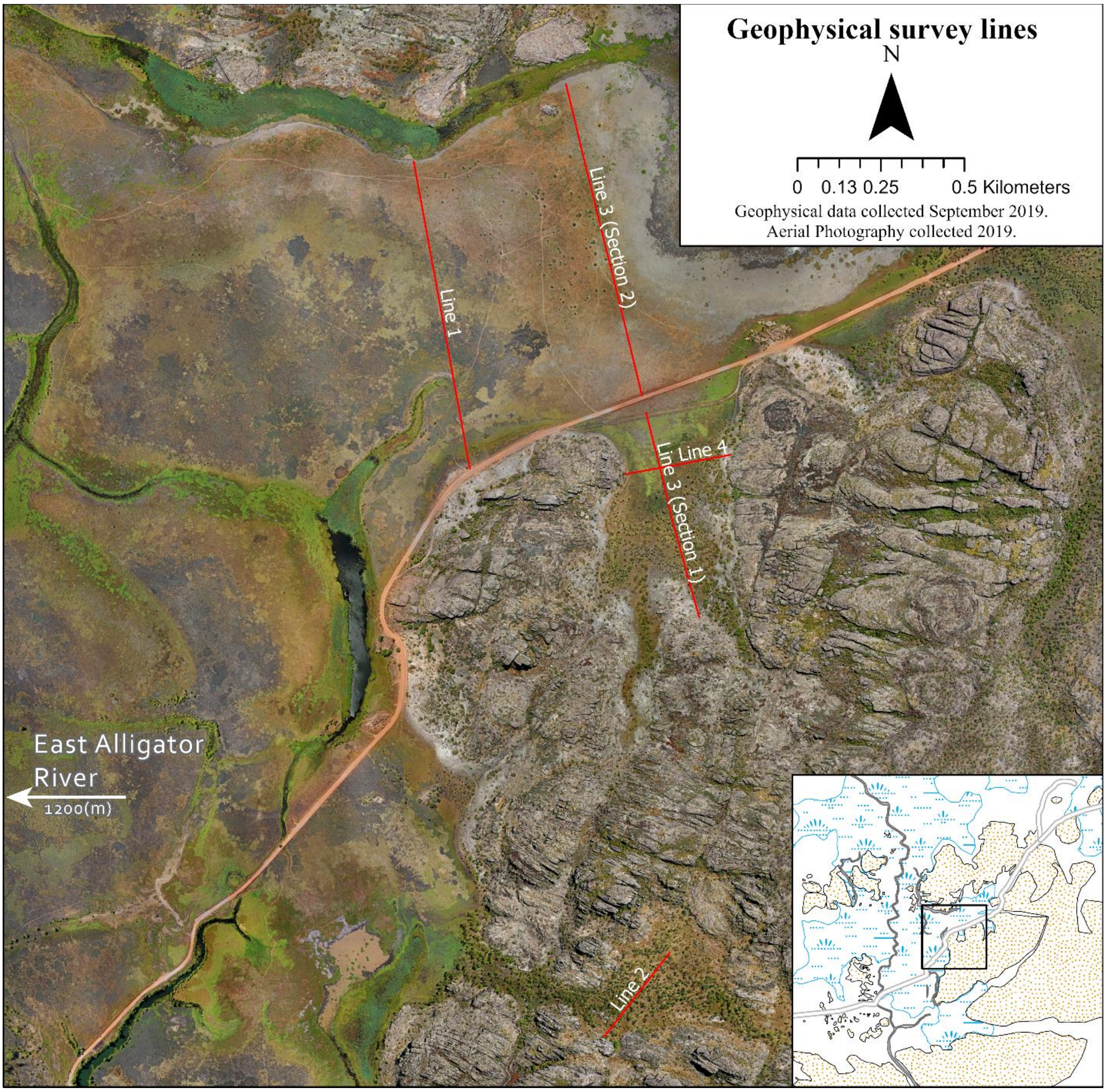


Figure 4.4 Geophysical survey lines in the greater Red Lily Lagoon Area on the southeast edge of the East Alligator River floodplain.

The position of each electrode was recorded using an Emlid RS+ RTK GPS. The reported line lengths have demonstrated that minor cumulative errors in the 5 m spacing have caused less than 3 m of placement discrepancy per line. Electrodes were hammered approximately 10–20 cm into the ground and then connected together with cable. A ZZ FlashRES-Universal resistivity instrument was used to conduct the ERT survey. The contact resistance of each electrode was measured prior to survey. When this contact resistance was too high for a given electrode, saline solution was poured onto the ground around the base of the electrode until sufficient contact resistance was achieved. In general, contact resistances of <500 ohm were achieved on the floodplain. The ERT instrument was used to inject current and measure potential through the connected electrodes. This injection sequence was conducted in three distinct array patterns for each line, which were Wenner, Schlumberger and Dipole-Dipole arrays. Each line was placed in a series of individual rolls of 64 electrodes spaced 5 m apart, after each roll the resistivity meter was connected to the next set of electrodes along the line with 32 electrodes overlapping each set of measurements.

Data Processing

The data collected during the ERT field survey was filtered to remove values with extremely high or low resistivity. The threshold for judging outliers was considered on a line by line basis. Inversions were undertaken using Res2D software and used the L1-norm (robust) for the model. The surface elevation in metres above sea level according to the Australian Height Datum (AHD) was provided for each electrode and included in the inversion file to allow the resistivity profiles to be topographically corrected.

As each individual ERT survey line's inversion result has a unique distribution of resistivity, choosing a display colour range must be done with the full survey in mind so as to allow meaningful comparison between the different lines. To achieve this, all individual resistivity estimations across all survey lines were combined into a single dataset and a colour range was calculated using a quantile approach. This approach divided the data into 16 classes distributing observations equally across set intervals. This produces a set of classes with unequal widths but an equal frequency of observations per class. Each individual inversion result was then displayed using a unique colour for each of the 16 calculated classes. This allows comparison between different lines as values within the same colour contour are likely to belong to the same subsurface feature class.

4.3.3 East Alligator River Channel Morphology

A LiDAR-derived DEM (Geoscience 2015) was used to map both the modern channel configuration as well as palaeochannels with remnant visible surface depressions across an extended area of the East Alligator region. To maximise visibility of palaeochannels, the DEM was displayed with a stretched histogram using the 'histogram equalise' method. This stretch method was chosen as it accentuates local contrast without affecting the global contrast of the image. Palaeochannels were interpreted through inspection of this DEM and satellite imagery available through ESRI ArcGIS Pro, and hand drawn.

4.4 Results and Geophysical Interpretation

4.4.1 ERT Results

Figure 4.5 shows an ERT profile of each survey line displayed with consistent resistivity colour contouring for comparison. The profiles are plotted against elevation and therefore the surface topography of each line is also visible in the profiles.

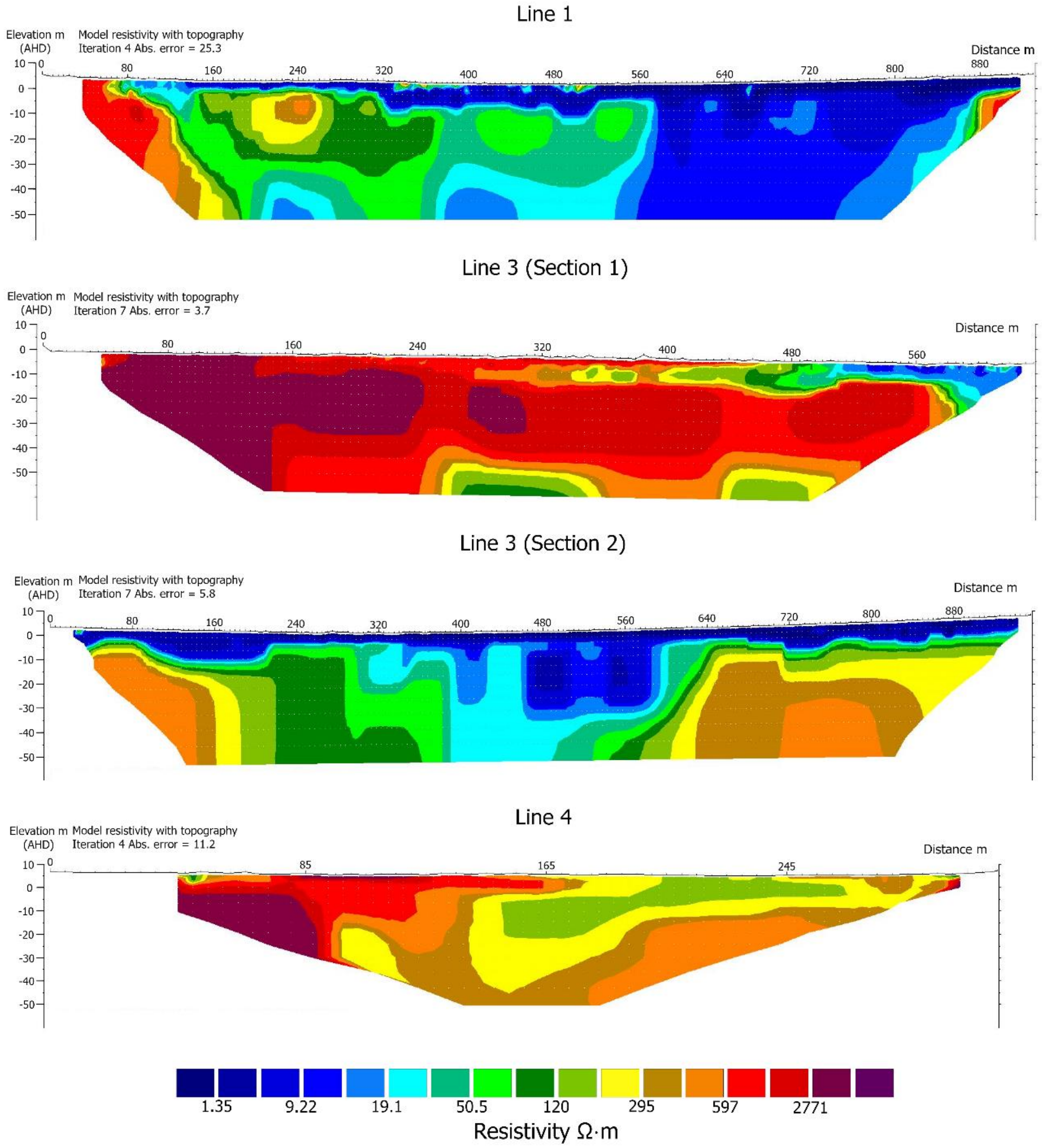


Figure 4.5 ERT profiles from all survey lines collected using the Wenner array. Resistivity has been contoured with colours grouping highly resistive features in dark red (>2771 Ω·m) and most conductive features in dark blue (<1.35 Ω·m). Areas of similar resistivity are shown in similar or the same colours presenting a map of resistivity facies in the subsurface.

4.4.2 ERT Interpretation

The ERT profiles in Figure 4.5 show the distribution of resistivity in the subsurface for each line. The inversion models were analysed in direct comparison to the expected depositional layers as derived from the floodplains of the South Alligator River and Magela Creek. Of the expected subsurface materials for the GRLLA floodplain environment, sandstone is likely to represent the feature with the highest resistivity closely followed by unconsolidated sand. Estuarine mud and organic sediments are likely to be less resistive. The interpretation of the underlying geomorphology for lines 1 and 3 can be seen in Figure 4.6.

ERT Floodplain Interpretation

Line 1 shows two extremely resistive features at the beginning and end of the line. These features have resistivity over 597 Ω·m. Based on their locations and shapes; these are interpreted as buried sandstone escarpments. The shape of these two features follows the forms of the exposed sandstone escarpments with their large sharply dropping terrace walls. This region of resistivity has been interpreted as Kombolgie sandstone, resistivity facies 'a' in Figure 4.6.

Adjacent to these sandstone features is a discrete area of moderate resistivity with a range of 197–597 Ω·m . These follow the form of the colluvial aprons of eroded sands from the Kombolgie sandstone which form against the escarpments. These regions of resistivity have been interpreted as colluvium, resistivity facies 'i' in Figure 4.6.

At the lowest levels of the profile is a region of distinct resistivity between 9 and 19 Ω·m. This feature has a surface elevation of around -4 m and has a geometry which correlates well to multiple incised fluvial channels. The surface height of this feature is within the elevation range of the pre-transgressive fluvial sediments characterised in Magela Creek (see Table 1 and Figure 4.3). This surface was described as sediments deposited in a freshwater fluvial system (Wasson 1992: 29). The three large channels in this surface agree with this interpretation. The deepest point of the deepest channel in this feature is around -32 m elevation. These regions of resistivity have been interpreted as fluvial sediments, resistivity facies 'c', 'd', and 'e' in Figure 4.6.

Adjacent to and overlying these sediments is a highly resistive feature that spans from 140 m along the line until 575 m and continues to depths of ~40 m. It has resistivity between 28 Ω·m and 597 Ω·m. This overlaps the previously interpreted colluvial sands. Interestingly, this feature is directly in line with the palaeochannel which contains the modern Red Lily Lagoon. There are a number of channels visible in the top of this resistivity facies unit. The resistivity range and the presence of surface channels along with the location under the palaeochannel of Red Lily Lagoon suggest that this feature is alluvial sand-rich sediments deposited by aggradation during periods of fluvial activity. This feature is interpreted as fluvial sediments, resistivity facies 'b' in Figure 4.6.

The deepest channels in facies 'c', 'd' and 'e' are at a depth that aligns with the sandy fluvial sediments associated with the Red Lily Lagoon palaeochannel. This suggests that this palaeochannel may have been the principal course of the East Alligator River in the past. The contrast of resistivity between these two channel beds suggests a difference in grain size between these channels. This difference in sandy sediment may indicate that Red Lily Lagoon was the principal channel of the East Alligator River during this time, carrying the major sediment load from the larger Arnhem Plateau.

The buried fluvial sediments are overlain by a layer of more conductive material with a resistivity range of 0.2 Ω·m (the lowest recorded) to 9 Ω·m. This layer occurs between elevations of -13 and 5 m and infills channel-shaped features. The depths and the decreased resistivity suggest this layer is made up of estuarine clays and muds produced by the Transgressive phase and subsequent mangrove development during the Big Swamp phase. The elevation range of this layer falls within the range of the mangrove sediments observed across the Magela Creek floodplain (see Figure 4.3) (Wasson 1992: 28–32,62). This layer has been interpreted as estuarine clay and sand, resistivity facies 'f', 'g' in Figure 4.6. These clays and sands occur adjacent to parts of the channel sediments of the Red Lily Lagoon palaeochannel. This suggests that while this channel predates the transgression, it continued acting as a distributary channel during the major mangrove infilling phase.

The transition from the Big Swamp to the contemporary freshwater floodplains has limited resistivity evidence. This absence may be caused by the resistivity of the materials being too similar to differentiate or the layer being too thin to have been modelled by the ERT inversion. There are several smaller pockets of higher resistivity materials (between 50 and 597 Ω·m) that occur sporadically along the top level of the resistivity profiles of the floodplain areas. These may represent evidence of the freshwater phase as they are in at the level of the contemporary surface and to a maximum depth of ~4 m. These features may represent palaeochannels from activity during the Freshwater phase with higher resistivity reflecting channel sediment deposits.

The interpretation of Line 1 can be compared directly to Line 3 (Section 2), which runs parallel to Line 1 and crosses the floodplains around 500 m east of Line 1. The same resistivity contours correlate to directly comparable subsurface features.

Line 3 (Section 2), which crosses the floodplain, shows two distinct regions of resistivity values that fall between 50 and 597 Ω·m (represented with green, yellow and orange colours in Figure 4.5) which are interpreted as sand-rich fluvial sediments. One of these two regions runs directly below Red Lily Lagoon and correlates to a similar feature in line 3 section 2 (seen in Figure 4.5 between 160 and 320 m along line 1 and 30 and 320 m along line 3 [Section 2]). The other sandy region does not correlate with Line 1. Inspection of the surface topography shows that there is a large, buried, meandering channel that hugs the sandstone escarpment on the northern edge of the floodplain. This is likely to be a continuation of the abandoned river channel in which Red Lily Lagoon is situated. The palaeochannel in which Red Lily lagoon is formed is therefore interpreted to have been the principal channel of the East Alligator River and acted as a distributary channel during the Big Swamp phase.

Between these two areas of higher resistivity is a lower resistivity feature with the geometry of two incised river channels. These two channels correlate with those in Line 1 that occur in the same band of lower resistivity fluvial sediments (facies ‘e’ incising through resistivity facies ‘c’ and ‘d’ in Figure 4.6). These channels are interpreted to have been incised into the pre-transgressive surface before being infilled with the much more conductive estuarine clays and mud of the Big Swamp phase. This feature is similar to the fluvial terrace structures of the pre-transgressive sediments observed in the Magela Creek floodplain (Wasson 1992: 29).

The estuarine sediments in Line 3 occur dominantly at elevations between -10 m and the surface level ~3.4 m. The small regions of higher resistivity which are interpreted as palaeochannels associated with the freshwater floodplain system are present in Line 3 at depths close to the surface but are less common than in Line 1.

ERT Valley Slope Interpretation

Line 3 (Section 1; Figure 4.5) descends the gradual slope of a large valley in the sandstone. This ERT line has been displayed with the same colour scheme as the other lines and is based on the combined resistivity range. This line is dominated by a geographically extensive, highly resistive feature with resistivity between 597 and 2771 Ω·m (displayed in red in Figure 4.5). This is interpreted to represent a shallow, shallowly dipping sandstone shelf that underlies this valley at a depth of approximately 2–15 m before dropping vertically a short distance into the floodplain. Some pockets of lower resistivity material occur within this sandstone shelf (represented in greens, yellows, and oranges at the bottom of Line 3 [Section 1] in Figure 4.5). These are likely to be part of the Kombolgie sandstone but represent localised variations in water saturation, porosity, or lithology. A band of highly resistive material, with resistivity between 597 and 1147 Ω·m, runs along the surface of the line in areas wooded with *Melaleuca* paperbark. Whilst these values are within the resistivity range interpreted as sandstone, observations of the sediment on the surface and the presence of mature trees suggest that this material is dry unconsolidated sand. The dry sandy sediment that fills the valley has been marked as colluvium, resistivity facies ‘h’ and ‘i’. The transition between these facies (‘h’ and ‘i’ in Line 3 [Section 2]) is interpreted to represent local variations in water saturation and/or salinity.

At 480 m along Line 3 (Section 1), where this valley reaches the level of the floodplain, a band of conductive materials overlies the colluvium. These materials fall into the resistivity range interpreted as estuarine clay and muds of the Big Swamp phase. This band continues across the flood plain in Line 3 (Section 2). The sharp contrast between these resistivity facies shows that the colluvial apron against the sandstone escarpment was in place at the time of the transgression and was then overlain with the more rapid infilling of clays and muds. The shallow depth of the sandstone shelf in this valley suggests that some of the bedrock may have been exposed on the valley floor during the Pleistocene.

Sea Level Rise and Floodplain Evolution

Mangroves in the modern Alligator rivers have been found to occupy an extremely restricted elevation range of 1 m below and 3.7 m above mean sea level (Wasson 1992; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986). A model of the sea level over time for this area was developed using the presence of mangrove materials in excavations of the South Alligator River floodplain (Wasson 1992: 141; Woodroffe et al. 1986: 124). Figure 4.6 shows some of the dated mean sea levels during the sea level rise following the LGM. On the basis of elevation, it is likely that in the GRLLA, the East Alligator River floodplain channels first became estuarine between 7.5 and 7 ka. By 6.5 ka, when the sea stabilised at its current level, sea water would have covered most of the modern floodplain especially during high tide. This led to the ubiquitous distribution of tidal flat sediments across the modern floodplains shown in the shallow subsurface by the ERT profiles.

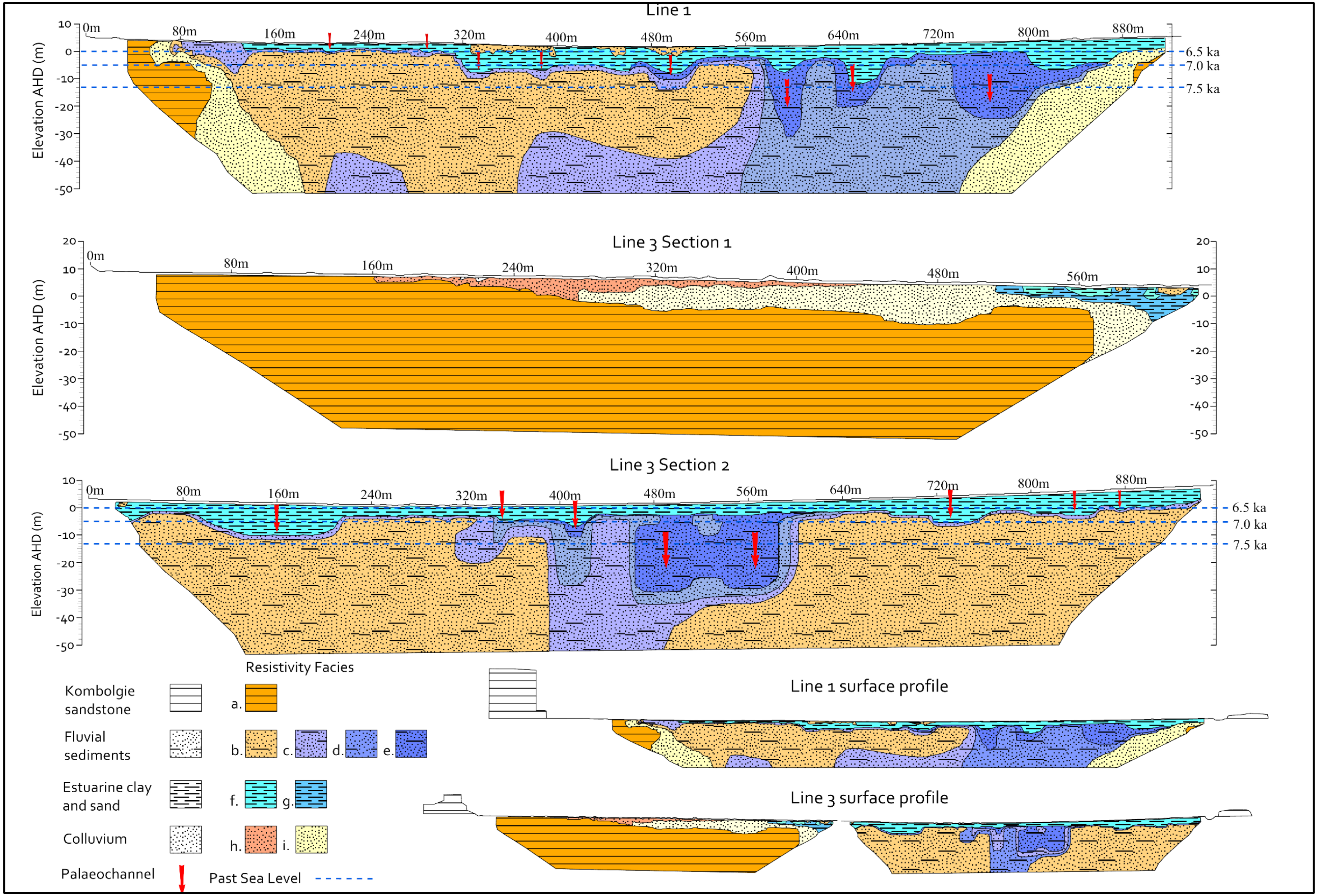


Figure 4.6 Geophysical interpretation displaying subsurface units, resistivity facies and surface profiles

4.4.3 East Alligator River Channel Morphology

Figure 4.7 shows a map of both the contemporary river channel and palaeochannels interpreted from the DEM and satellite imagery. Regions where former river meanders are visible on the surface have been labelled A through C. These regions occur where the bedrock topography allowed the formation of past river meanders and show a gradual progradation of the meandering section of the river morphology seaward.

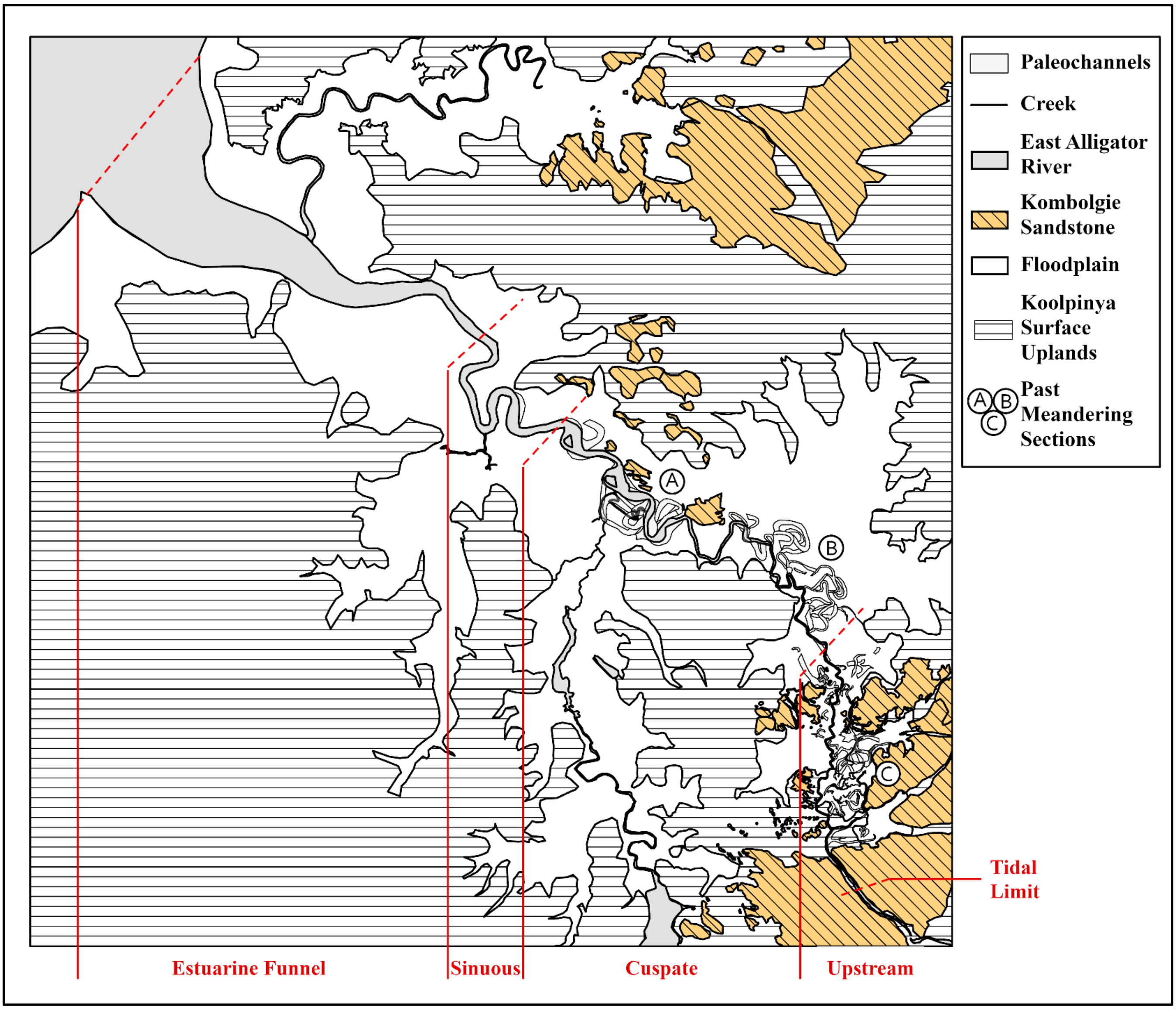


Figure 4.7 East Alligator River channel and palaeochannel morphology

4.5 Discussion

4.5.1 Pre-transgressive Landscape

The ERT results present a detailed palaeogeography of the GRLLA over the 60 ky of Aboriginal occupation. The most striking feature in this landscape is a sandstone escarpment that stood above the level of the Pleistocene land surface that is now completely buried (See Line 1 in Figure 4.6). This escarpment was at a highly accessible location that was episodically adjacent to major river channels before the transgression and presents a likely location for human occupation during this time. If the subsurface geomorphology of the GRLLA is replicated elsewhere in the more than 280 km of floodplain-adjacent escarpment in Arnhem Land, it is likely that a great number of Pleistocene and Holocene sites of human habitation are now buried.

The results from Line 3 (Section 1) shows that this valley has a cover of unconsolidated sand over a bedrock surface that slopes towards the floodplain. The rate of the sediment accumulation in this valley cannot be inferred through the ERT results; however, the stratigraphic relationship between this facies and the floodplain suggest that some of this material was deposited prior to the Big Swamp phase. This, in combination with the relatively thin accumulation of sediment, suggests a relatively slow sediment accumulation rate in this region.

The ERT data show that sediment is being deposited in different ways (and at different rates) in different parts of the GRLLA, including the sheltered sandstone escarpments (MN05), sloping valleys within the larger sandstone formation (Line 3 [Section 1]), and the floodplains below the sandstone escarpments (Line 1 and Line 3 [Section 2]). This model is important in understanding the distribution of dates for occupation of shelter sites. All the excavated shelters were located on colluvium formed against the sandstone escarpments and elevated above the level of the transgressive infill and resulting sediments of the Big Swamp phase. These areas are good excavation targets on the bases of having slow rates of sediment infill and being close to the modern land surface, but they are not geographically extensive and only represent one aspect of the region's palaeogeography. This limited dataset has important implications for understanding settlement strategies over the human history of this region (Allen and Barton 1989; Brockwell et al. 2011; Hiscock 1999).

4.5.2 Transgression and Big Swamp development

The ERT interpretation confirms that the Big Swamp mangroves extended to the outer reaches of the East Alligator River floodplain (and hence to the edge of the Arnhem Land escarpment) in the GRLLA. Some authors have suggested that this might be the case (Wasson 1992;

Woodroffe et al. 1986). However, direct testing had not been conducted outside of areas close to the main channel of the South Alligator River and Magela Creek. This presence of Big Swamp sediments to the floodplain edges strongly supports the model of Woodroffe et al. (Woodroffe et al. 1986: 118) of rapid transgressive infill even in distal parts of the floodplain. This rapid and extensive flooding would have had a significant impact on mobility and amount of land available for inhabitants of the GRLLA during the mid-Holocene.

The ERT profile demonstrates that the early period of the transgression was characterised by estuarine intrusion into the existing channels of the pre-transgressive surface. The rate of vertical aggradation of these channels must have been exceeded by the sea level rise by 6.5 ka. At this point sea water covered the entire floodplain, followed by mangrove development. This may provide a possible alternative mechanism for the presence of marine shellfish taxa found in Ngarradj Warde Djobkeng, Malangangerr and Nawamoyn, which have been interpreted as being traded from coastal origins as opposed to locally sourced (Schrire 1982; Woo 2020: 203,209,225).

This extensive transgression event, and the subsequent decline of mangroves and establishment of salt flats in the region, must have had major implications for mobility and resource availability. This result strongly supports our contention that pandanus nut $\delta^{13}C$ (Florin et al. 2021) dated to this period reflect a response to increased standing water associated with the dramatic extents of marine influence and the effect on freshwater aquifer drainage. This model also shows the likely impact on pandanus availability due to loss of habitable land, which may explain the scarcity of excavated samples from this time.

4.5.3 Sinuous and Cuspate Phases

The river morphology and palaeochannel mapping from the LiDAR data demonstrates that the configuration of the East Alligator River has changed significantly since its transition from a freshwater to a tidal-dominated estuary. The tidal-dominated estuary section has followed the overall straight-meandering-straight configuration. However, during the earliest periods of the Sinuous phase, the mixed-energy zone was clearly much closer to the stone plateau as demonstrated by the concentration of remnant river meanders in this region. This is consistent with the ERT interpretation that the influence of the transgression reached as far as the sandstone plateau in front of Red Lily Lagoon. Several meandering sections (Figure 4.7 sections a, b, c) show the gradual movement of this mixed-energy zone downstream. These sections of river meander are likely to be separated by areas of bedrock control preventing meander development. This model of past river configuration goes further to demonstrate the major landscape changes over the human history of the region even in the past 5 ky.

The changes in the fluvial system during the Cuspate phase developed out of the erosion of past meandering sections and required the mixed-energy zone to have prograded before this development was possible. During this time the extensive salt flats that extended to the sandstone plateau are likely to have slowly transitioned to the seasonally inundated grasslands of the contemporary floodplain. However, there is no direct evidence of this development found within the data collected for this research.

4.5.4 Approach Assessment and Limitations

The ERT results allow for a clear interpretation which strongly matches the existing models of the subsurface from South Alligator River and Magela Creek regions. The major limitation to the ERT was the inability to distinguish between the clays and organic sediments from the Big Swamp phase and the freshwater floodplain phase due to their similar resistivity character. Despite this, the depths of the estuarine clays and sands layers (facies 'f' and 'g') clearly match the depth ranges for the Big Swamp stratigraphy from the existing models.

4.5.5 Implications for Archaeological Research in West Arnhem Land

This research has several important implications for archaeological research in Western Arnhem Land. Firstly, we have demonstrated that the Pleistocene landscapes of this region can be effectively mapped using non-invasive methods. This has important implications for locating new sites but also for developing a more nuanced understanding of the regional palaeogeography, and its impact on human behaviour.

Based on the results of this study, all Pleistocene sites in western Arnhem Land on the edge of the escarpment were probably immediately adjacent to the ocean and, subsequently, mangrove swamps at some point during the transgression. This has important implications for the palaeogeographic settings of these sites, which must be considered when interpreting changes in stone artefacts, food resources and the isotope composition of biogenic materials from this period.

Further, the model of sandstone valleys being filled with a slowly accumulating apron of locally derived sand which we observe in ERT lines 2, 3 and 4 is important for understanding the archaeology of Western Arnhem Land more broadly. All archaeological sites with Pleistocene dates within the region (Madjedbebe, Ngarradj Warde Djobkeng, Malangangerr, Nawamoyn, Bindiarran and Birriwulk) are associated with similar colluvial aprons adjacent to sandstone escarpments at elevations higher than the floodplain. This is in keeping with our proposed model that this is the only position in this landscape that Pleistocene sediments will exist close to the modern land surface in the region.

Finally, our survey reveals the tantalizing prospect of a buried escarpment with adjacent thick accumulations of Pleistocene aged sediment. This geomorphic feature almost certainly contains abundant archaeological sites. However, its position beneath up to 9 m of floodplain sediment means that it probably remains out of reach of archaeological surveys with modern technology.

4.5.6 Future Directions

The timings of the mangrove development detected by ERT was inferred from the sea level curves developed from the published excavations in the South Alligator River and Magela Creek regions (Wasson 1992; Woodroffe 1988; Woodroffe 1993). However, direct investigation and dating of the landforms characterised for the pre-Transgressive phase and the subsequent freshwater floodplain development would help to characterise and validate the models developed through this research.

The 5 m electrode spacing of the survey allowed large cross sections of the floodplain to be covered; however, this came at the cost of resolution. This was suitable for the aims of this research to characterise floodplain stratigraphy in a broad sense. A more detailed ERT survey with shorter electrode spacing could allow the further characterisation of the morphology as well as further detection and characterisation of palaeochannels. The landscape profile also has the potential to show likely locations for middens. Middens may be detectable using ERT, further increasing the potential for ERT investigation of the floodplains for site detection (Kenady 2016).

4.6 Conclusions

ERT is a rapid, low cost, non-invasive method that can characterise large areas of the landscape. ERT data can be used to develop landscape models that are useful in understanding known site locations as well as predicting new site locations. Combined ERT- and LiDAR-based modelling characterised the major landscape changes from the late Pleistocene to the late Holocene of the Greater Red Lily Lagoon Area. This characterisation helped connect broader landscape models to the floodplain surrounding Red Lily Lagoon and extended previous models of the transgression and its impacts on previous land surfaces. Directly demonstrating the burial of a sandstone escarpment in close proximity to a major stream channel present during the late Pleistocene and early Holocene is an important step to modelling the landscapes and human settlement strategies. The characterisation of the colluvial valleys and aprons of the sandstone formations demonstrates a useful model in understanding the locations and taphonomy of the known older pre-transgressive occupation sites such as Madjedbebe.

4.7 Acknowledgements

Jarrad Kowlessar is the recipient of a Flinders University Postgraduate Scholarship. Ian Moffat and Daryl Wesley were both supported by George Chaloupka Fellowships from the Museum and Art Gallery of the Northern Territory. Daryl Wesley is the recipient of an Australian Research Council Discovery Early Career award (project number DE170101447) funded by the Australian Government. Ian Moffat is the recipient of an Australian Research Council Discovery Early Career award (project number DE160100703) funded by the Australian Government and a Flinders University Early Career Researchers Award. This research was approved by Northern Land Council permit #79130 and via Flinders Human Research Ethics application #7704. Thank you to the Njanjma Rangers who provided outstanding support for the research.

CHAPTER FIVE

Chapter 5: A changing perspective: the impact of landscape evolution on rock art visibility

Jarrad Kowlessar[1], Daryl Wesley[1], Mark Willis[2,1], Ian Moffat[1], Tristen Jones[5], Shay Wrigglesworth[3,4], Alfred Nayinggul[3] and the Njanjma Rangers

1. Archaeology, College of Humanities, Arts and Social Sciences, Flinders University
2. Sacred Sites Research
3. Njanjma Rangers
4. Kakadu National Park
5. Archaeology, School of Humanities, Faculty of Arts and Social Sciences, The University of Sydney

An earlier version of this chapter has been submitted for publication the Journal of Archaeological Method and Theory

Approximate contribution of co-authors: Jarrad Kowlessar (65%), Daryl Wesley (5%), Mark Willis (5%), Ian Moffat (5%), Tristen Jones (5%), Shay Wrigglesworth (5%), Alfred Nayinggul (5%) and the Njanjma Rangers (5%)

5.1 Abstract

Arnhem Land, one of the oldest dated regions of human activity on the Australian continent, also holds one of the greatest assemblages of rock art in the world. Indigenous artistic practice in this region has continued since before the Last Glacial Maximum through to the modern day, a period of some 28 thousand years, during which time the region has undergone incredible environmental and palaeogeographical changes. Rock art research in the area however, has not yet been conducted with direct reference to these local palaeoenvironmental changes, relying instead on larger regional models. This paper addresses this issue, applying detailed geomorphological palaeogeographic modelling conducted in the Red Lily Lagoon region in Eastern Arnhem Land, to the spatial analysis of rock art site placement in this important cultural landscape. The resultant elevation, land cover and visibility modelling reveal significant changes in the site placement strategies of the rock art in the region, highlighting changes in four key phases of the past environmental history, spanning from the late Pleistocene to the late Holocene.

5.2 Introduction

When rock art assemblages are considered at a landscape scale, it is possible to analyse spatial patterning as a means to infer site selection processes (Bradley 1991, 1997; Bradley et al. 1994b, 1994a; Hartley and Vawser 1998; Ross and Davidson 2006; Schaafsma 1985: 261–263; Whitley 1998). This approach has been explored for north-western Arnhem Land where Wesley et al. (2017) demonstrated the links between the style of motifs, their inferred chronology, and their geomorphological placement. At a broader scale, regional studies have assessed rock art distribution and variation (see May et al. 2018; McDonald and Veth 2012; Taçon 1989b; Taçon 1993; Taçon et al. 2020), and linked rock art to changing environmental conditions to establish regional chronologies (see Chaloupka 1993). Recent geomorphological characterization of the Greater Red Lily Lagoon Area (GRLLA), a province of exceptional archaeological significance in Arnhem Land, Australia (see Figure 5.1), has made an environmental interpretation of the rock art sites in this landscape possible with an unprecedented level of detail (Kowlessar et al. 2022b). In this work, Kowlessar et al. (2022b) connected four distinct past environmental phases with distinct palaeogeographical configurations, that is paleolanscapes, of the East Alligator River region. Figure 5.1 shows the East Alligator River region along with the GRLLA study area.

An innovation proposed in this paper is the linkage of rock art distribution to digital modelling of these palaeolandscapes in the East Alligator River region, utilising high resolution elevation data, an approach which has yet to be fully explored. This will be achieved with the inclusion of detailed topographic elevation modelling, paleoenvironmental modelling and viewshed analysis.

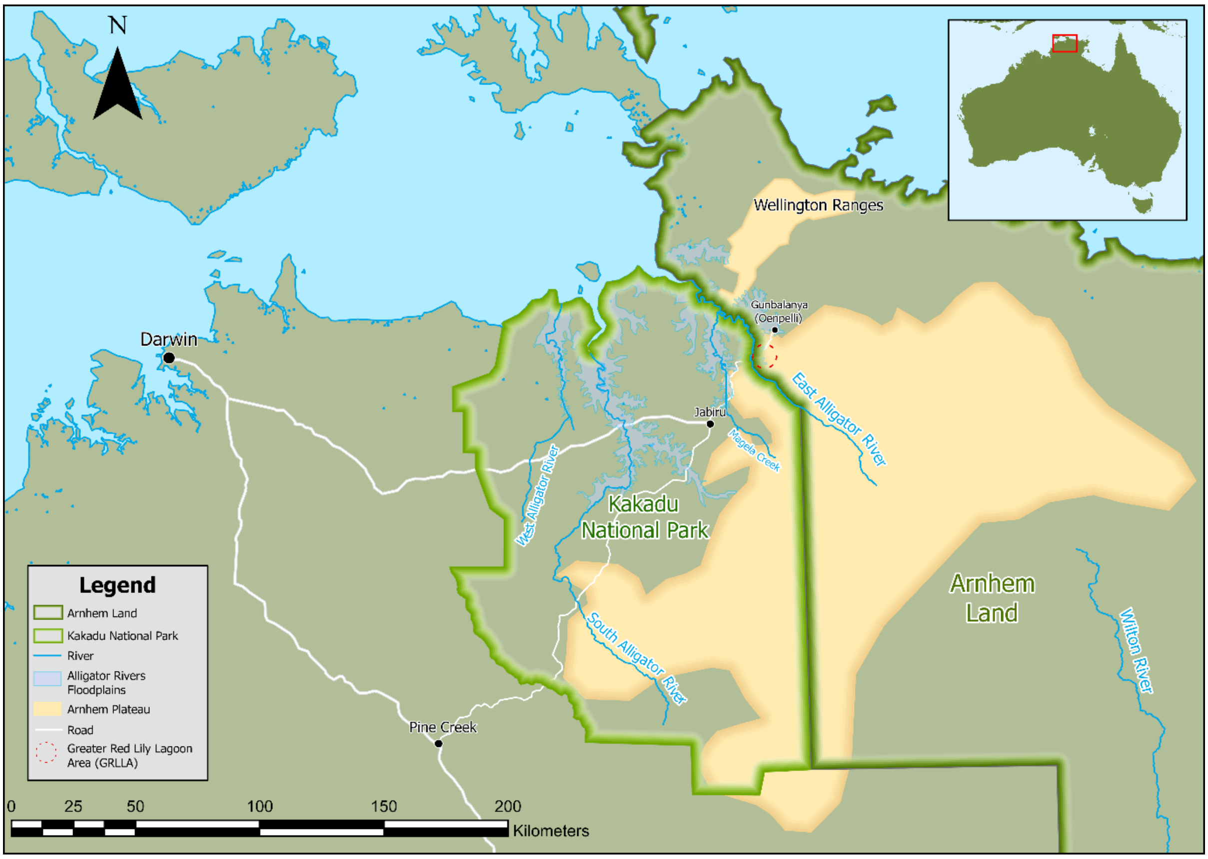


Figure 5.1 Map of the Study area within the larger region, showing the Alligator rivers, river floodplains, Kakadu National Park and Arnhem Land along with the Arnhem Plateau

The rock art of the GRLLA has great heritage significance, and along with the high density of Indigenous cultural places, the region is currently being assessed for inclusion on the National Heritage List (Nayinggul 2016). The rock art in the GRLLA has been directly dated to the Pleistocene–Holocene transition and production has continued to modern times (Jones et al. 2017b). This deep history of art production in the region provides a unique interpretive context given the scale of environmental and geographical changes that have occurred over this time. By analysing the artistic assemblage within their contemporary environments, this paper provides unique insights into settlement strategies and human adaptations throughout these periods, adding to the current understanding of this significant area both in practical and methodological fashions.

5.2.1 Landscape and Visibility Analysis of Rock Art Site Placement

Traditionally, regional landscape patterning of rock art sites has been used to gain insights into past settlement strategies, clan boundaries and social complexities, as well as to formulate broad environmental relationships (McDonald and Veth 2012; Taçon 1993). Such regional studies of rock art sites have primarily followed broader hunter-gatherer mobility and aggregation concepts by studying the variation of artistic styles within the spatial distribution of sites. In this way, artistic style is viewed as arising as a cultural function and tied closely with social identity (Conkey 1980: 609; McDonald and Veth 2012: 92; Smith 1994: 10-11; Taçon 1993). This association of distinct styles with social and cultural groups leads to the interpretation of style as a form of information exchange (Smith 1994; Wiessner 1984; Wiessner 1989; Wiessner 1990; Wobst 1977). This perspective views style as a culturally controlled, shared visual language, which symbolically encodes information through visual and contextual means that can be understood only from an emic perspective (Smith 1994; Wiessner 1984; Wiessner 1989; Wiessner 1990; Wobst 1977). Whilst the exact and intended meaning of an artistic inscription may be difficult or impossible to accurately infer from an etic perspective, the distribution and variations in style have nonetheless, been used to provide insights into past human social organisation and settlement strategies when interpreted as indicators of cultural groupings (Conkey 1980; Domingo Sanz 2012; McDonald 2005; McDonald and Veth 2006; Ross and Davidson 2006; Wiessner 1984).

Concepts of hunter-gatherer societal structures, settlement strategies and social complexities have also been approached at a regional level through the analysis of variation and distribution of material culture (Conkey 1980). These notions have been directly associated with the concepts of mobility and aggregation, which refer to the spreading apart and coming together of people within a distinct social group/society across physical space (Conkey 1980). Mobility in this regard refers to the overall range of activities of a particular group of people and may describe nomadic, fragmented occupation strategies, whereas aggregation describes the coming together of these otherwise fragmented groups that together form a distinct connected society (Conkey 1980). From these two concepts, ecological conditions and associated exploitation strategies can be inferred, with larger range associated with lower resource density, whilst higher degrees of aggregation and sedentary occupation are associated with areas of higher resources and carrying capacity (Conkey 1980; Lewis 1988).

Following this approach, higher degrees of variation within the art record can be associated with increased population size, aggregation, and social complexity. This has been argued to occur within fertile regions with rigid territorial systems and complex kinship/social structures and is indicated by an increase in the social information encoded through variations in art (Lewis 1988; McDonald and Veth 2012). A widespread distribution of more homogenous artistic style may instead correlate to more open social networks and scarcity of resources, likely associated with harsher environments and associated exploitation strategies (Lewis 1988).

Ecological changes are another means of gaining insight into the social structures of past hunter-gatherer societies, and indeed, may often have acted as the catalysts for social changes and structural developments (Jones 2017; Morwood and Hobbs 1995). This is especially applicable in the analysis of rock art, which is an inherently visual and spatial phenomenon and therefore ties into personal identity and relationship to landscape. When style is associated with culture and social identity, this reveals a contextual shared visual language inherent to that style. This form of information exchange is therefore strongly associated with the intended context of a cultural expression (Wiessner 1989; Wiessner 1990; Wobst 1977).

In the case of rock art placed on an unmovable location within the landscape, this context includes both what is inscribed as well as where and when it was inscribed (Johnston 2018: 88). This human relationship with land goes farther than a simple function of the ecological landscape and ties more deeply into human perceptions and experiences. Extending analysis of style into the landscape locations and patterning of rock art site placements, extends the ways in which information can be encoded via art into a complex culturally distinct relationship to landscape that can be inherently considered part of the overall style (Bradley 1991; Domingo Sanz 2012). In this way, art is painted in a given space with the intention of it being viewed at that location and to a culturally emic perspective. Therefore the specifics of the rock art space itself may carry part of the information exchange, suggesting that an analysis of space needs to focus on the human perspective and the experience of being in the location where the rock art marking and viewing occurs (Bradley 1991).

Visibility is a property of a given space that has been used to provide insight into the human experience and sense of presence at a given location (Llobera 2003; Robinson 2006; Robinson 2010; Tilley 1994; Wheatley and Gillings 2000; Wienhold and Robinson 2019). Recently, visibility has been used to help interpret placement of rock art in a landscape (Acevedo et al. 2019; Díaz-Andreu et al. 2017; Fairén-Jiménez 2007; Fairén 2010; Intxaurbe et al. 2020; Ruiz et al. 2021). The analysis of rock art through visibility has been based around two major approaches: a rock art site's visibility from the landscape (i.e., hiddenness vs openness), and the visibility of the landscape from a rock art site. In the case of rock art these two are not directly reciprocal, as an individual motif may be placed in such a way as to be hidden or concealed from easy view but a human present and viewing/inscribing the motif may still have an excellent view of the landscape from such a location (Domingo et al. 2020).

The visibility of rock art from the landscape has been interpreted as being associated with its function as a signal. This site placement consideration is clearly associated with social complexity and directly relates to the communication of information at given locations. This may be intended to mark territorial boundaries, indicate the presence of local resources or signal aspects of spiritual landscapes, or perhaps to perform more than one of these functions (Jones and May 2017). Such placements will clearly correlate to areas of human mobility and transit. Negative correlations may indicate deliberate hiddenness. The difficulty of assessing the hiddenness of rock art still leaves a significant interpretive challenge in understanding the purpose of this concealment. Often, perceived hiddenness of art at a site has been interpreted as a deliberate choice by the artist with the intention of restricting access to this art for reasons often interpreted as cultural secrecy (Domingo et al. 2020). Domingo et al. (2020) have questioned the assumptions that hidden or low-visibility sites directly relate to an intended restriction of access or secrecy of such a site, supported by a number of Australian examples where this assumption is not met. Furthermore, the range at which the rock art features are distinguishable from the landscape is highly limited compared to the broad view of the landscape afforded from a rock art inscription (Fairén-Jiménez 2007: 291). For this reason, the purpose of signalling may not explain prominent site placements in a straightforward manner due to associations with specific locations based on inherent properties. These considerations create a significant challenge for the analysis of the visibility of rock art sites from the surrounding landscape and the implications of any such visibility.

Visibility of a landscape from the locations of rock art sites has been analysed using a variety of approaches to interpret site selection intentions. Patterns within the visibility of landscape can be inferred through a cumulative viewshed approach (Acevedo et al. 2019; Fairén 2010; Wheatley 1995). This approach looks at a variety of sites that make up an archaeological landscape and combines the viewshed (mapped areas of visibility) from each of these sites to analyse what areas of the landscape are visible from multiple sites. A landscape area which is visible from a higher number of individual sights may be interpreted to be associated with the site selection process, possibly indicating a connection between the art and visibility aspects of that area. Such patterns of landscape visibility have been interpreted as a function of territorial control, having shown in some cases to be associated with vantage points that provide visibility over the low-lying areas which provide the easiest routes for physically traversing the landscape (Fairén-Jiménez 2007; Ruiz et al. 2021). Such territorial control is therefore argued to be a lookout location where art is also inscribed rather than a space of singularly dedicated cultural activity.

Alternatively, visibility has also been interpreted in terms of mobility, with site selection that prefers areas with extensive views of the surrounding landscape, argued to be associated with high mobility patterns of landscape use (Fairén-Jiménez 2007; Fairén 2010). Patterns of site selection which favour limited visibility of the surrounding landscape may instead speak to more focused landscape use and possible more intensive occupation (Fairén-Jiménez 2007; Fairén 2010).

Regardless of the specific interpretations, the landscape visibility from a location is clearly a component of human sense of presence, which is central to the activities being undertaken there (Tilley 1994). However, in the case of extended temporal usage of an area, visibility analysis must be conducted with an understanding of the geomorphological and environmental changes the landscape may have undergone between the site formation event and the modern day (Wheatley and Gillings 2000). Unless changes in topography, vegetation and surface features are considered, the calculated visibility will be inaccurate. For this reason, visibility approaches of rock art sites such as those found in the GRLLA, should be considered in direct consultation with accurate geomorphological modelling.

5.2.2 Rock Art of the Greater Red Lily Lagoon Area

Several distinct artistic styles occurring throughout Arnhem Land have been proposed by rock art researchers. These styles have been developed based on repeatedly occurring traits which have been observed and formally described into a set of defined typological styles. Broadly agreed categories include Dynamic Figures, Post Dynamic Figurers, Northern Running Figures, Simple Figures with Boomerangs, Yam figures, Simple Figures, Large Humans, Large fauna, Early X-Ray, Complete Figure Complex, Beeswax Figures and X-Ray Figures (Chaloupka 1993; Chippindale and Taçon 1998; Taçon et al. 2020). Variations exist within each of these styles, however, these groups broadly unify figures drawn in a certain way and which depict a common set of subject matter. Table 5.1 describes each of these distinct styles, limited to those which have been found to appear in the GRLLA study area.

Table 5.1 Rock Art Styles of Arnhem Land found within the Greater Red Lily Lagoon Region.

Style	Description
Dynamic Figures	This manner of depiction typically illustrates Human Figures which are painted in a dynamic pose illustrating activity often running. Usually depicted without genitalia, though female figures are illustrated with breasts. Often depicted with 'bustle' or skirt hanging from the waist and holding spears or boomerangs. (Chaloupka 1993; Chippindale et al. 2000)
Post Dynamic Figures	Human figures that resemble Dynamic figures but have more passive pose and more simplified linework. (Chaloupka 1993)
Northern Running Figures	This manner of depiction typically illustrates Human Figures, usually painted in exaggerated running posture with elongated S-shaped bodies Male depictions are most common, with depicted genitalia and head dresses. Distinctive solid line drawings with muscular legs painted with solid linework. (Chaloupka 1993; Jones and May 2017)
Simple Figures with Boomerangs	Human figures are painted with highly simplified linework, usually a single straight line for each limb and torso. Depicted holding boomerangs, these are only distinguished from the subsequent 'Simple Figures' by the inclusion of this older boomerang technology. (Chaloupka 1993; Lewis 1988)
Simple Figures	Painted in the same style as Simple Figures with Boomerangs but painted without weapons or with more recent technology such as spears. (Chaloupka 1993; Lewis 1988)
Yam Figures	Figures painted with a distinct linework pattern and always depicting Yam's. Sometimes painted as anthropomorphic human/yam hybrids.
Large Human	Depictions of humans drawn in a large style with complex linework often with decorative infill patterns and elements.
Large Fauna	Large figures which depict fauna, often macropods. These are distinguished from 'Early large naturalistic fauna' figures which are argued to be older with distinct red ochre linework (Chaloupka 1993; Jones et al. 2020).
Early X-Ray	Considered the earliest depictions of artwork in the region which show internal organs. This style depicts fauna with internal details often optic nerve and spine depicted. These are more limited in internal detail than the more recent X-Ray style.
Complete Figure Complex	This style groups several distinct sub-styles which all represent the recent Freshwater period. These styles include complex decorative infill patterns and depict humans, spirits, and fauna. The energetic figures which are a simplified human depiction drawn with a distinct style of stick-like line work are also included in the Complete Figure Complex (Taçon 1989a).
Beeswax Figures	Figures that are formed from dots made of beeswax which are applied to a rock face. These figures can be both geometric and figurative designs (Brandl 1968).
X-Ray	Figures depict fauna with detailed infill patterns and internal organs and bones visible. These figures often depict butchered animals (Chaloupka 1993).

5.2.3 Environment and Rock Art Chronology

The GRLLA is situated on an important boundary between the ‘stone country’ of the Arnhem Plateau Kombolgie sandstone formation, and the vast floodplains of the Alligator rivers (see Figure 5.1 and Figure 5.2). Figure 5.1 provides the broader region whereas Figure 5.2 shows the sandstone escarpment and the floodplains of the East Alligator river in more detail. Human occupation of the sandstone escarpment and floodplains interface has been demonstrated for over 60,000 years, with multiple occupation sites in the area greater than 20,000 years old (Allen and Barton 1989: 102; Clarkson et al. 2017; Clarkson et al. 2015; Schrire 1982: 110–145). Rock art production in Arnhem land has been demonstrated for at least 28,000 years but likely has occurred for much longer (David et al. 2013a). Despite the longevity of artistic practice in the region all directly dated in situ art has been inscribed after the Last Glacial Maximum (LGM) and chronological estimates place all known examples into this period (Johnston 2018; Jones et al. 2017a; Jones et al. 2017b; Jones et al. 2020; Taçon et al. 2020). The environmental history of the area has shown substantial change over this period of rock art inscription with major landscape changes associated with post glacial sea-level rise and precipitation changes during the Holocene (Kowlessar et al. 2022b; Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985). Figure 5.2 shows the GRLLA study area along with the local sandstone escarpment and floodplains of the East Alligator river.

SOURCES: ESRI, GARMIN, FAO, NOAA, USGS

Figure 5.2 East Alligator Region, Greater Red Lily Lagoon Area, East Alligator River floodplains and Kombolgie sandstone formation

The Alligator River region has been categorized into four environmental phases for the period of time following the Last Glacial Maximum (LGM) through to the modern day. These phases are Sea Level Rise phase, Marine Transgression (hereby referred to as Transgression phase), Big Swamp phase, and Freshwater Floodplain (hereby referred to as the Freshwater phase). These phases were chosen to directly compare the rock art chronology of Arnhem Land with the environmental chronology.

Sea Level Rise Phase 14,000–8,000 BP

The GRLLA of northwest Arnhem Land was a fluvial landscape throughout the Quaternary, with rivers running from the Arnhem Plateau highlands down through the low-lying valleys to the north (Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985). The nature of the fluvial systems in these low-lying valleys, which underlie the contemporary floodplains, varied through the glacial cycles of the Quaternary. These glacial cycles led to changes in both precipitation and base level, which would have led to changes in these fluvial systems. Any such changes driven by glacial cycles over the Quaternary are currently poorly understood. Additionally, cycles of post-glacial transgressive scouring have erased many of the traces of previous fluvial systems (Wasson 1992). During the LGM this landscape underwent its driest phase, with the low-lying valleys dry and much lower in relative elevation than present day. The recent geophysical modelling of the geomorphology of the GRLLA has demonstrated the pre-transgressive fluvial landscape (Kowlessar et al. 2022b). This fluvial landscape would likely have been active in the area since the previous interglacial cycle with smaller creeks and streams running through open woodland (Kowlessar et al. 2022b).

Arnhem Land has been identified as a Pleistocene refugia when compared to surrounding regions during the LGM (Veth 1989). Despite the relative resource availability compared to surrounding regions, human activity here during the Pleistocene has been characterized as having been highly mobile with flexible foraging strategies employed in the cooler and drier landscape dominated by open eucalypt forests and tropical savanna (Clarkson et al. 2017; Clarkson et al. 2015; Woo 2020). The end of the LGM around 14 ka saw a period of increased humidity and significant global sea-level rise. The sea-level rise flooded huge areas of the Sahul shelf which had connected the Australian mainland to Papua New Guinea, creating the contemporary Gulf of Carpentaria. This Sea Level Rise phase represents the sea-level rise as it occurred distantly from the study area which lasted until 8 ka when marine water finally reached the GRLLA. During this time the now coastal areas of West Arnhem Land and the GRLLA transitioned from 350 km to 50 km inland from the coast (Taçon and Brockwell 1995; Williams et al. 2018).

It is clear from the amount of land lost that a great number of people must have been displaced which is reflected by an increase in population density (Williams et al. 2018). These people are likely to have represented a variety of separate and unique social and territorial structures (Blainey 1975: 90–91; Veth et al. 2021; Williams et al. 2018). This process of change may have been fast enough to be directly observed in the span of a lifetime (Taçon and Brockwell 1995; Williams et al. 2018). This change inevitably resulted in alterations to social boundaries, trade networks, and resource availability and may have resulted in a total restructuring of boundaries and clan relationships (Blainey 1975: 90–91; Veth et al. 2021; Williams et al. 2018). The high number of groups and significant language diversity along the north coast of Australia has been argued to have emerged from a social restructuring occurring in direct relationship to the dramatic climate change events that began around this time and continued into the mid Holocene (Blainey 1975; Jones 2017; Veth et al. 2021; Williams et al. 2018).

Within Arnhem Land rock art, the 'Dynamic Figures' are associated with the arid period before the marine transgression reached the GRLLA. However, these figures may have already been occurring further seaward (Chaloupka 1993; Chippindale and Taçon 1998; Reeves et al. 2013a; Reeves et al. 2013b; Yokoyama et al. 2001). This artistic style has not been directly dated but has been placed at this point in the chronological order based on superimposition and relative dating results. The Dynamic Figures are predominantly male human figures painted in dynamic poses, usually depicted in hunting scenes featuring macropods, emus, and other terrestrial fauna (Chaloupka 1993). Some association has been made with the headdress and bustle depictions of this style and those found in contemporary Papua New Guinea, which may suggest an association from a time before the complete flooding of the Sahul Shelf (Chaloupka 1993: 110). The distribution of the Dynamic Figure style covers the entire Arnhem Plateau from its western most reaches all the way to Wilton River to the east and covering the plateau's northern extents (Wellington Ranges) to the southern extents of the Plateau (Johnston et al. 2017: 113). This extensive distribution has been used as an indicator of past social–cultural boundaries and inferred lifeways suggesting a dispersed and mobile population (Lewis 1988). This broad social open mobile lifeway is in keeping with expected foraging strategies in the harsh arid conditions of the environment contemporary to the Dynamic Figures original inscription (Lewis 1988). With origins overlapping or emerging from postglacial sea-level rise, this style may be indicative of socio-environmental adaptive response and subsequent changes to social complexity and symbolic identity. This idea has been put forward for the highly environmentally comparable Kimberly region's Gwion figures, which have been argued to have been a contemporary style to Arnhem Land's Dynamic Figures (Veth et al. 2021; Yokoyama et al. 2001).

The first appearances of large battle scenes within the rock art seem to be associated with this time (Taçon and Chippindale 1994). While sea level would not yet have reached this area, a substantial amount of the adjacent continental shelf would have begun to be covered leading to mass migration and social restructuring which may have led to conflict and even warfare (Taçon et al. 1995:121; Lewis 1988: 90; Blainey 1975:90–91). These battle scenes have been more recently interpreted as depictions of ritual combat as opposed to open conflict or warfare (Johnston 2017; May et al. 2018). This interpretation further supports a model of significant and distinct sociocultural changes with complex ritual and symbolic representations associated with this time.

Blainey (1975:90–91) argued that a sea-level driven migration over a long-time span likely followed river corridors as people retreated further inland. This may identify the Alligator River region as an important point of inevitable contact between locally established groups and displaced people, especially towards the end of this period. The GRLLA is located at the boundary between the lowlands of the river valley and the stone plateau, which has a distinct change in river gradient and ecology. Ecotones such as this, that lie between the coastal planes and sandstone plateau, have been identified as having a higher density of occupation than other locations across the landscape (Allen and Barton 1989; Hiscock 1999; Schrire 1982; Wesley et al. 2017: 25). Ecotones also have a general abundance of biodiversity, an important factor in Indigenous subsistence practices (Wesley et al. 2017: 25). Furthermore, in the case of riverine and sandstone environments these both have major impact human mobility with riverine corridors providing a highly traversable vector through sandstone environment.

Recent analysis of Dynamic Figures has suggested that there may be more complexity and variation within this class than previously detected. Variations which were previously ascribed to chronological change may instead be best accounted for by regional variability (Johnston et al. 2017). Another explanation for these regional variations may reflect differences from individual artists and not represent a cultural regional separation (Johnston et al. 2017: 122). This model would suggest that during this time only a small number of individual artists may have been active and that they may have had large contributions to the collective artistic assemblage (Johnston et al. 2017: 122).

The Dynamic Figures are followed by a style called ‘Post Dynamic Figures’. These human depictions are illustrated in more static poses and often more solid infill patterns than the Dynamic Figures (Chaloupka 1993). Recent analysis using machine learning indicates that these styles are closely related, which likely indicates a gradual shift between these forms rather than a punctuated stylistic innovation (Kowlessar et al. 2021). The earliest directly dated rock art style in the Arnhem Land Region is the Northern Running Figures (NRF). These figures depict humans, usually in a running and combat or hunting posture, and have a minimum age of 9,400 cal. BP (Jones et al. 2017). The NRF style has a very limited distribution across Arnhem Land which is centred on an area around the East Alligator River (see Jones and May 2017). Whilst this is the only radiometrically dated style in the region, a detailed relative chronology of styles has been established through a study of superimposition of motifs in the area (Chaloupka 1993; Chippindale and Taçon 1998; Taçon et al. 2020). This chronology places the two distinct styles of human depiction, Dynamic Figures and Post Dynamic Figures, earlier than the NRF style (Chaloupka 1993; Chippendale and Taçon 1998). These three styles have therefore been associated with this Sea Level Rise phase.

Large Naturalistic Style (LNS) fauna paintings are thought to have been associated with this older phase and likely predate these styles (Jones et al. 2020). Although the age of the LNS is unknown, it has been estimated to be in the pre-estuarine environmental phase, based on superimposition chronology (Jones et al. 2020). LNS depictions can appear throughout the chronology and are difficult to be clearly identified to a particular phase (Jones et al. 2020).

Transgression Phase 8,000–6,500 BP

The marine transgression into the low-lying valleys and existing fluvial setting of the Alligator River region occurred around 8,000 BP and continued until around 6,500 BP when sea levels stabilized. The transgression rapidly and extensively flooded the low-lying valleys of the Alligator rivers (Woodroffe, et al. 1993; Wasson 1992:55-56,141). This flooding has been modelled as a total filling with ocean and effectively represents at least a temporary coastline along the edges of the modern floodplain valley (Woodroffe, et al. 1993; Wasson 1992:55-56,141). The extent of this transgression occurred all the way into the GRLLA, directly up to the sandstone escarpment (Kowlessar et al. 2022b). This phase saw a dramatic loss of land and suggests that significantly less land was available during the peak of this transgression than during the modern day.

The NRF style is likely to have occurred well into this phase and followed by motifs of human figures called 'Simple Figures with Boomerangs' (Chippendale and Taçon 1998). Simple Figures with Boomerangs are a style of human figures that became increasingly simplified and now contain a diversity of postures, depictions of activity and material culture (Chaloupka 1993; Chippendale and Taçon 1998). Recently, radiocarbon dating of materials associated with painted rock art panels showing Simple Figure motifs have demonstrated the possibility that this style may have origins closer to 9,260–9,540 cal. BP (David et al. 2017). Despite the ambiguity of its first appearance, the Simple Figures with Boomerangs style is still dominantly associated with this Transgression phase. Large Fauna depictions continue to be painted through this phase.

The Rainbow Serpent motif's appearance also occurs around this time, and some argue this is directly associated with this marine transgression (Taçon et al. 1996:121; Lewis 1988). Stories of the powerful Rainbow Serpent demonstrate that it is responsible for large scale transformations and represents a natural force of both creation and destruction (Taçon et al. 1996:121). The Rainbow Serpent has also been argued to be an important force of cultural unification, and its ceremonial use can represent unity among groups and highlight aspects of shared heritage and origins (Taçon et al. 1996:121; Lewis 1988; Taylor 1990). If this association with the sea-level change event is to be followed, the cultural role of the Rainbow Serpent clearly shows a distinct change in social complexity and social structures directly emerging from this event, with aspects of both conflict and unity involved. Elements of the Early X-ray style may have also appeared during this phase (Jones et al. 2017a; Jones et al. 2020).

Big Swamp Phase 6,800–4,400 BP

Areas flooded by the marine transgression were quickly colonised by mangroves allowing the development of a widespread mangal (community of mangrove species) forest (Woodroffe, et al. 1993). This forest has been demonstrated to have rapidly and completely infilled the flooded valleys all the way to the sandstone escarpment beside Red Lily Lagoon (Kowlessar et al. 2022b; Woodroffe 1993). The timing of the mangal forest development varies among the Alligator Rivers, although dating control is poor. Mangroves reached their maximum upstream extent in Magela creek, a tributary of the East Alligator River, by 4,400 BP. This extends the Big Swamp development phase in the East Alligator River for a longer timespan than that in the South Alligator River, indicating a decline beginning around 5,300 BP as the sinuous phase of the river morphology began (Wasson 1992:55-56,141). For much of the Big Swamp phase total coverage of the contemporary floodplains must have occurred (Kowlessar et al. (2022b). The sedimentation caused by these mangroves infilled and overlie sections of sandstone escarpment along the floodplain edges within the GRLLA (Kowlessar et al. 2022b). This indicates that many of the possible occupational locations of the early part of the Big Swamp phase, and all of the period of human occupation of the floodplain that predate this phase, are now buried (Kowlessar et al. 2022b).

A clear shift in archaeological site usage during the Big Swamp phase has been observed within the excavated assemblages of the area (Allen 1989; Allen and Barton 1989; Clarkson et al. 2017; Clarkson et al. 2015; Hiscock 1999; Jones 1985; Schrire 1982). During this shift, mobility was reduced, population density increased, and site usage lasted longer than the previous sporadic, seasonal site occupation (Hiscock 1999: 94; Allen and Barton 1989; Clarkson 2017). Shellfish became the dominant food resource as shown by the appearance of shell middens at the occupied sites on the edges of this huge mangal forest (Allen and Barton 1989; Clarkson et al. 2015; Schrire 1982; Woo 2020). A distinct change in lithic technology is also associated with this phase, indicated by the appearance of spear points and steeply retouched flakes (Allen 1989; Allen and Barton 1989; Clarkson et al. 2017; Clarkson et al. 2015; Hiscock 1999; Jones 1985; Schrire 1982: 250-251; Woo 2020: 225). This increase in point production may indicate a move towards spears as a dominant hunting tool and away from boomerangs. Spears are thought to be more associated with fishing, whereas boomerangs are associated with hunting large animals on open plains and in woodlands. This technology transition is therefore a possible indicator of adaptation from the arid pre-transgressive landscape to the marine and estuarine environments of the transgressive phase (Brockwell et al. 2011; Lewis 1988; Chaloupka 1993).

The extensive mangal forest covering all low-lying areas in the region must have caused a major restriction to mobility (Allen 1996: 198, 201; Allen & Barton 1989: 104). This restriction may have made crossing the lowlands difficult or even impossible and limited movement and settlement location to the plateau’s margins and valleys, along with limited lowland corridors among tidal floodplains (Allen & Barton 1989: 104).

The changes in lithic technology through this period coincides with the appearance of new technologies depicted in the rock art, including a high diversity of spear types and spear throwers (Lewis 1988; Chaloupka 1993; Chippendale and Taçon 1998). This technological change separates the older Simple Figures with Boomerangs style from the emerging Simple Figures style depicting these newer technologies. Examples of Simple Figure motifs are considered to be the older ‘Simple Figures with Boomerangs’ style when they are depicted with boomerangs or among scenes with boomerang depictions. Otherwise simple figures are typically assigned to the more recent ‘Simple Figures’ class (Lewis 1988; Chaloupka 1993; Chippendale and Taçon 1998). Within the rock art record this phase also saw the proliferation of estuarine fauna species which are best hunted using spears (Chaloupka 1993; Wesley et al. 2017).

The Simple Figures represent a highly varied style of rock art and several regional substyles (Kowlessar et al. 2021; Lewis 1988; Taçon 1993: 114). These regional styles have been subjectively inferred through carefully constructed regional typologies (Lewis 1988: 34-38) as well as more recently detected and characterised using machine learning (Kowlessar et al. 2021). Both approaches have characterised the Simple Figures regional styles as being collectively part of a larger Simple Figures class which occurs over the entire Arnhem Plateau, yet still distinctly separable from one another based on regional stylistic differences within this class. This increase in regionalism within the rock art may speak to a cultural change occurring throughout Arnhem Land and social reorganisation that is coincidental with the Big Swamp phase.

Yam Figures appeared during the Big Swamp phase along with Early X-ray style art. Yam figures are a distinct style of linework and subjects usually depict yams as well as human–yam hybrids. Early X-ray art predominantly depicts animals drawn to show internal features such as bones and organs. Recently, Early X-ray art has been directly dated using radiocarbon dating on overlaying mud wasp nests and calcium oxalate mineral crusts. This date provides a minimum age of 5,068–6,666 cal. BP for this style. This age confirms this style's placement within the Big Swamp phase and raises the possibility of an earlier appearance of this style (Jones et al. 2017a).

Large Human figures join large fauna during the Big Swamp (Chaloupka 1993; Chippendale and Taçon 1998). This demonstrates an increase in the diversity of artistic styles during this period further indicating changing roles of art and social complexity during this time. Simple Figures, Yam Figures and Large Human Figures show multiple ways of drawing humans practiced simultaneously even within the same region, and indeed, sometimes on the very same painted panel (Chippindale and Taçon 1993). During this time, Yam Figures have been argued to represent activities of the spiritual domain, whilst Simple Figures are used for those related to the material domain (Chippindale and Taçon 1993: 106). This implies a complexity to the role of art and ways in which it is used to encode and communicate information.

Freshwater Phase 4,400 Onwards

The peak of mangrove dominance during the Big Swamp phase was followed by a highly variable environmental period dominated by the effects of the sedimentation caused by the extensive mangroves systems. The mangroves facilitated significant sediment accretion as the El Niño-Southern Oscillation (ENSO) monsoon system reactivated, increasing denudation of the sandstone escarpment and highlands around the flooded valley (Wasson 1992; Woodroffe 1993). Eventually this led to shoreline progradation which left the GRLLA region only occasionally exposed to marine water and made the habitat unsuitable for mangroves. This process was spatially complex and caused a great deal of variation in the local mangrove habitats (Wasson 1992: 55–56; Woodroffe 1993). The mangroves were replaced by saline mud flats, which may have created equally vast areas of resource-scarce land (Hiscock 1999; Hogarth 2015). This phase is often called the Sinuous phase as the Alligator rivers entered a phase of sinuosity as the flow regime significantly changed as a result of increased rainfall, stable base level and low fluvial gradient caused by shoreline progradation (Kowlessar et al. 2022b; Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985).

Peak lithic production occurred during this time, related to the stress of these major changes to resource availability, with an increase in tools for managing risks associated with research scarcity or unpredictability (Hiscock 1996). A decline in long-term occupation has been interpreted from the excavated materials of rock shelters situated within the sandstone escarpments on the floodplain fringes (Allen 1989; Allen and Barton 1989; Brockwell et al. 2011; Clarkson et al. 2015; Hiscock 1999; Schrire 1982; Woo 2020). During this decline in occupation of the sandstone shelters, there was an increase in open sites and a general shift in population towards the coast (Bourke 2004; Brockwell 2006; Brockwell et al. 2011; Guse 2005; Hiscock 1999). This period of site abandonment and changing technology was likely driven by a resource scarcity brought about by the development of hypersaline mudflats which remain where mangroves have receded. These mudflats offered few resources when compared with their mangal predecessors. It is unclear how long it may have taken for these mudflats to become the freshwater floodplains we see today, but this process was driven by shoreline progradation, the El Niño-Southern Oscillation monsoon seasonality, and freshwater dominance during the wet seasons that followed. This mangrove recession and Sinuous phase of the East Alligator River morphology overlapped.

As progradation moved river marine energy seaward, new regions of sinuosity developed further seaward, and the flow rate through old river meanders increased as fluvial dominance overtook marine forces in these upstream extents. The increased flow rate through past river meanders erodes riverbanks causing sharp cusps in the channel morphology. This period, referred to as the Cuspate phase followed the Sinuous phase of river morphology and demonstrates the river’s transition into the seasonally flooded freshwater-dominated system of the modern day.

The establishment of the freshwater floodplains may be associated with the return of more dense occupation of the sandstone fringes (Brockwell et al. 2011; Hiscock 1999). as the floodplains are seasonally inundated through the strong tropical wet/dry seasonality which followed the LGM. Consisting of grasslands during the dry season and freshwater wetlands during the wet season, the floodplain margins of the East Alligator River record an increased population within the last 2000–1000 years BP (Hiscock 1999; Jones 1985) as occupation became focused on abundant freshwater floodplain resources including freshwater fish and birds (Brockwell et al. 2011; Hiscock 1999; Shine et al. 2016; Shine et al. 2015; Wesley et al. 2017).

The East Alligator River morphological phases (sinuous and cuspate) and the Freshwater phase together, are synchronous with the final chronological phase of the rock art styles. During this time, the diverse and abundant Complete Figure Complex style emerged, along with Beeswax figures and the world-renowned X-Ray rock art, a highly decorative and complex successor to the Early X-Ray style (Chaloupka 1993; Chippindale and Taçon 1998). Art of this phase has been clearly linked to this environmental period through the depiction of freshwater flora and fauna along with hunting scenes and detailed interactions with the floodplain environments (Chaloupka 1993). As the most recent rock art style, and a close connection to contemporary artistic practices in Western Arnhem Land, the X-Ray style provides ethnographic insights regarding personal, social and spiritual identity, encoded in these artworks (Taçon 1989a; Taylor 2008b, 2008a). This period of art displays a vivid use of colour and decorative patterns directly associated with the artist's personal clan identity (Taçon 1989a: 209). Such clan designs are present predominantly in depictions of humans, and less often in animals where they act as decorations rather than species identification, therefore playing a role in both the spiritual identity of the artists and the subjects, along with the associated stories depicted (Taçon 1989a: 209). These clan designs have been said to have been passed down from Ancestral Beings and their use continues to be associated with their power and association with clan country (Taçon 1989a; Taylor 2008b, 2008a). Indeed, within this most recent period of rock art there are also direct depictions of sacred Ancestral Beings (Taçon 1989a). This use of art to mark places with signals of personal identity, as well as with linkage to spiritual stories associated with specific locations, is a distinct signalling behaviour which clearly demonstrates these important and functional links to artwork placement throughout the landscape.

5.2.4 GRLLA Settlement and Site Selection Patterns

Wesley et al. (2017) assessed settlement and site selection patterns through time using rock art styles and the site's relative height and geomorphic context as the primary data. This grouped sites throughout the GRLLA based on art style chronology into early (20,000 to 8,000 BP), middle (8,000 to 3,000 BP), and late (3,000 BP to recent) phases. Each site was given a geomorphological context, either hilltop, hillside, or base, determined by their relative position on the sandstone escarpment. This allowed total rock art motif densities to be estimated, along with the rate of new discrete painted shelter/boulder art sites added per year and the relative site placement patterns based on the escarpment positions. Wesley et al. (2017) found that the late phase showed the highest percentage of individual motifs, but the middle phase showed the highest percentage of active sites. There was a tendency for sites to be located on hillsides during the early phase but evenly distributed from escarpment base to hilltop during the late phase (Wesley et al. 2017). Note that Wesley et al. (2017) included the NRFs in the middle phase, and although they were subsequently dated to be active in the early phase, were likely continued in use during the middle phase (Jones 2017; Jones et al. 2017b). Jones and May (2017) presented additional data for the placement of the NRF figures based on geomorphological classes of the sandstone escarpment. The classes were boulder plain, outlier base, outlier slope, and outlier top. This research included data from GRLLA as well as sites from elsewhere. NRFs were demonstrated to have been most frequently positioned on outlier tops, and secondly on outlier slopes with less placements in the other locations. Jones and May (2017:59) noted that the outlier top is the highest elevation class of these categories but note that this trend may be biased by overpainting occurring during subsequent phases which use the lower regions of the sandstone more dominantly.

Wesley et al. (2017) and Jones and May (2017) argued that these patterns in site placements and changes through time reflect changing mobility and occupation patterns but may also be influenced by taphonomy. Both these approaches use geomorphological classes which have some analogy to elevation. However, two sites of the same geomorphological class ‘Hill Top’ may have significantly different elevations and these classes only distinguish very local, directly adjacent, trends in elevation. For this reason, there is merit to investigating elevation of sites directly.

5.2.5 Geomorphology and Land Cover Classes

Kowlessar et al. (2022b) provided a detailed model of the GRLLA palaeogeography throughout the major periods of environmental change between the late Pleistocene and modern day. These findings provide insights into the relationships between modern day land cover classes and prior geomorphological conditions. The colluvium slopes that infill valleys in the Kombolgie Sandstone escarpment have been demonstrated to have accumulated over previously exposed bedrock. The floodplain has been demonstrated to be underlain by a pre-transgressive land surface up to 10 m below the current surface level. A buried sandstone escarpment which represents the front escarpment of the Kombolgie formation within the GRLLA during the Pleistocene underlies the floodplains. Importantly, this escarpment shelf lies below contemporary paperbark woodlands so it can be mapped by proxy from the surface. Similarly, the backswamps that currently retain surface water even during much of the dry season overlie previously exposed sandstone escarpment. Understanding these contemporary land cover conditions as indicators of past landscape conditions is critical for interpreting rock art site placement over the period of human occupation in the GRLLA. Table

5.2 shows the land cover classes as defined in this study and their connection to the landforms within the study area.

Table 5.2 Landscape classes as defined in this study based on typical environmental compositions in the Northern Territory (after Finlayson et al. 1989; Needham 1984; Senior and Smart 1976; Sweet et al. 1999; Taylor and Dunlop 1985; Wilson et al. 1990a; Wilson et al. 1990b)

Landscape Classes	Vegetation	Geology	Landforms
Sandstone	Complex mosaic of woodlands mixed with shrublands with *E. miniata* (Darwin Woolly Butt), *E. tetrodonta* (Stringybark) *Corymbia* sp. (variable-barked Bloodwood), low open woodland with *Plectrachne pungens* (Curly Spinifex) open-hummock grassland	Kombolgie subgroup: sandstone consists of cross-bedded quartzose sandstone, medium to very coarse and siliceous; conglomerate of quartzite and vein quartz clasts	A western sandstone escarpment with a broken cliff up to 200 metres high. Surface is mostly bare rock or shallow sandy soil. Forms sandstone tors, platforms, major escarpment features, and large rounded highly weathered hills.
Colluvium	*E. miniata* (Darwin Woolly Butt), *E. tetrodonta* (Stringybark), *E. bleeseri* (smooth stemmed bloodwood), *E. tectifica, E. tintinnans* (Salmon Gum) open woodland with *Sorghum* sp. grassland understorey	Tertiary sediments of the plains overlie widespread Tertiary laterite consisting of sand, silt, soil, ferruginous laterite	Undulating sandy plains consisting of the most extensive unit in the region. Located between coastal and estuarine plains and the sandstone plateau. Support woodland to tall forest with tall grasses.
Floodplain	Mixed closed-grassland and sedgeland consisting of *Eleocharis* swamp, *Oryza* swamp, *Hymenachne* sp and *Pseudoraphis* sp grassland and *Fimbristylis* sedgeland	Alluvial and estuarine sediments	Sediment actively prograding over the finer deposits of the estuarine plains. Seasonally inundated during the annual wet season. Extensive freshwater swamps and paperbark forests..
River/Creeks/Lagoons	*E. papuana* (Ghost Gum), *E. polycarpa* (Swamp Bloodwood) woodland with grassland understorey. Wild rice (Oryza *rufipogon*) and the spike rush (*Eleocharis dulcis*) found in lagoons	Fluvial, alluvial, and estuarine sediments	Inland sections of the major river courses. Commonly forms levees and inter-channel bank deposits.

Backswamp	*Melaleuca* forest, *Oryza* swamp, *Hymenachne* sp and *Pseudoraphis* sp grassland and *Fimbristylis* sedgeland	Alluvial and estuarine sediments overlying sandstone	Permanent wetlands forming over outer edges of the floodplain with sediments overlying shallow sandstone.
Paperbark Swamp/Woodland	*Melaleuca* forest with *Melaleuca leucadendra, Melaleuca cajuputi and Melaleuca quinquenervia* low open-woodlands and mixed shrublands	Tertiary sediments of the plains overlie widespread Tertiary laterite consisting of sand, silt, soil, ferruginous laterite	Open Forest growing on undulating sandy plains with poor drainage often with underlying sandstone bedrock confining drainage.
Open Eucalypt Woodland	*E. miniata* (Darwin Woolly Butt*), E. tetrodonta* (Stringybark), *E. bleeseri* (smooth stemmed bloodwood), *E. tectifica* open forest with *Sorghum* sp. grassland understorey.	Koolpinyah Land Surface - Sand, silt, soil, ferruginous laterite	Located between coastal and estuarine plains and the sandstone plateau. Support woodland to tall forest with tall grasses. Tertiary sediments of the plains overlie widespread Tertiary laterite
Monsoon Vine Thicket	Closed canopy evergreen forest with mixture of palms and deciduous low vine thicket	Sand, silt, and soil of the Koolpinyah Land Surface and shaded gorges of the Kombolgie Subgroup formations.	Vine forests grow in some gorges and on plains where there are permanent springs.

5.3 Methods

5.3.1 Data Collection and Organisation

Field surveys conducted in 2015, 2018, and 2019 recorded 103 rock art sites across the study area that were included in this analysis (Jones et al. 2017a; Kowlessar et al. 2022a; Wesley 2016; Wesley et al. 2017). These sites were recorded with photography and a handheld Global Navigation Satellite System (GNSS) was used to record site locations. A record of the motif styles, features and subject matter was made in the field. Many of the sites were also recorded using the photogrammetry method outlined in Kowlessar et al. (2022a). The chronological age of the sites was inferred through an analysis of the styles depicted in the rock art. Four major chronological periods associated with distinct environment conditions were selected, which are Sea Level Rise, Transgression, Big Swamp, and Freshwater environmental phases. The presence of a motif with a style associated with one of these phases was used as selection criteria to generate four subsets of the data thereby grouping the rock art data by contemporary environmental phases. Large Fauna was not included in these chronological subsets due to the ambiguity in correct chronological identification between different temporal styles which are still ongoing debate (Jones et al. 2020). Simple figures were included in the Transgression and Big Swamp phases, although there is a possibility that this style may have originated in the terminal end of the Sea Level Rise phase (9,260–9,540 cal. BP) (David et al. 2017). Sites that exhibited motif styles associated with multiple phases were included in the subset of each of these phases. As such, the combined total of each of these subsets exceeds 103, as some sites were active during multiple phases and included in both subsets. Table 5.3 shows the styles recorded and their grouping based on their environmental phase.

Table 5.3 Styles and environmental phase grouping

Phase	**Sea Level Rise phase 14 – 8 ka**	**Transgression phase 8 – 6.5 ka**	**Big Swamp phase 6.8 – 4.4 ka**	**Freshwater phase 4.4 ka onwards**
Styles	Dynamic Figures Post Dynamic Figures Northern Running Figure	Northern Running Figure Simple Figures with Boomerangs Large Fauna	Simple Figures Yam Figures Large Human Large Fauna Early X-Ray	Complete Figure Complex Beeswax Figures X-Ray

5.3.2 Land cover Analysis

A supervised land cover classification was performed for the entire study area. Every area of the study bounds was categorized into one of the following labels: River, Floodplain, Backswamp, Colluvium, Sandstone, Monsoon Vine Thicket, Open Eucalypt Woodland and Paperbark Woodland. Figure 5.3 demonstrates these land cover classes and their landscape and geomorphological context along with subsurface features (Kowlessar et al. 2022b).

This classification was performed using manual tracing of satellite images, and aerial photography along with ground visits and photographic records for validation. The data were converted into image data with a pixel size of 2.37 m and values from 1 to 8 representing the land cover class for each pixel.

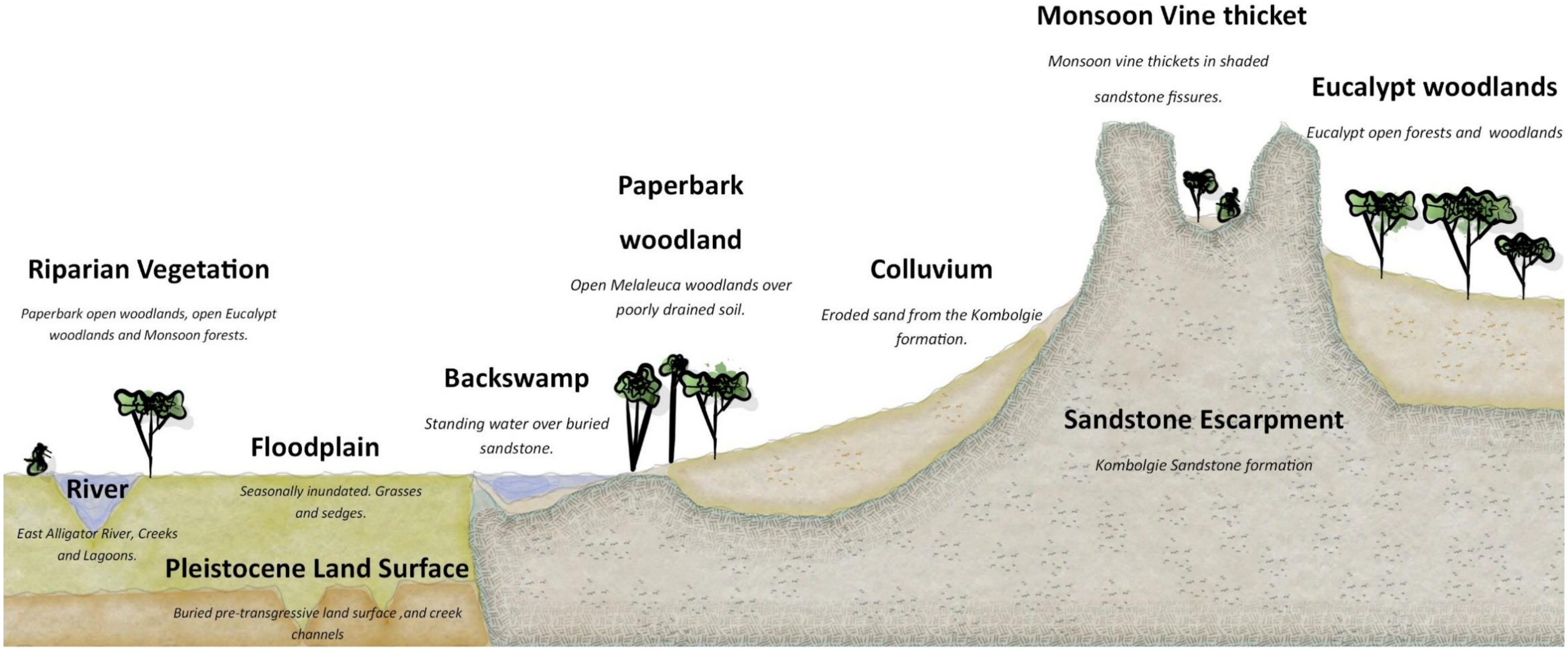


Figure 5.3 Conceptual diagram of land cover classes and geomorphology of the GRLLA

5.3.3 Visibility Analysis

A digital elevation model (DEM) was used for the study area that was a composite of three elevation models derived from Shuttle Radar (SRTM1S13E132V3 and SRTM1S13E133V3 images courtesy of the U.S. Geological Survey), LIDAR (Geoscience 2015) and drone-based photogrammetry (Kowlessar et al. 2022a). These had a spatial resolution of 20 m, 5 m and 6 cm pixels, respectively, and were resampled to a consistent 2.62 m pixel size. This composite was used to maintain a complete coverage of the study area which was 175.93 km^2.

A second DEM was derived from this contemporary elevation model by adjusting the major geomorphological component elevations based on the results presented in Kowlessar et al. (2022b). This second DEM aims to represent the best model of the pre-transgressive surface elevations based on the average depths determined by Kowlessar et al. (2022b). Areas of contemporary floodplain were lowered by 7 m from their contemporary elevations reflecting the removal of mangrove sediments. Backswamps were lowered by 1 m to reflect the removal of sediments overlaying a shallow buried sandstone surface. Floodplain areas with paperbark swamps and woodlands were lowered by 5 m reflecting a shallow buried sandstone escarpment. All other surface areas were left at their contemporary elevations.

The rock art sites were placed on the DEM based on their GNSS position. The exact site positions were supervised and adjusted based on the aerial photography and DEM to choose the most appropriate observer vantage point on a site-by-site basis. Site placement was made as a single point per site. This point was placed in a location close to the rock art panel(s) as central to the site as possible, in a location where a free-standing person may be offered the best view of the landscape. This was chosen to represent the locations for the viewshed as opposed to the rock art panel(s) directly. The point which represented this observer at each site was 1.75 m above the ground surface (elevation was derived from the underlying DEM) to represent a standing and attentive person. Visibility was calculated for the entire DEM from each site using the 'visibility analysis' tool in ArcGIS Pro (ESRI) software. This method produces a raster dataset of the same spatial resolution (pixel size) as the input DEM for each observer point (rock art site), with pixels represented by 1 for visible areas and 0 for non-visible areas. This viewshed dataset represents the areas of the DEM that are visible from a given rock art site. A second visibility analysis was conducted for the sites using the second DEM surface which represents an interpreted pre-transgression elevation model for the area.

The total area (km^2) of land surface visible from each site was calculated as the number of pixels with a value of 1 (indicating visibility) multiplied by the pixel area (6.86 m^2) and finally divided by 10^6 to give area in square kilometre units (km^2).

The separate site viewsheds were added together using raster math to generate a cumulative viewshed raster dataset for each of the four environmental phases of interest. Two separate cumulative viewsheds were produced for the Sea Level Rise and Transgression phases, representing the visibility based on the contemporary elevation and the interpreted pre-transgressive elevation. Each cumulative viewshed raster dataset has the same resolution as the input DEM and has a value for each pixel equal to the total number of sites active during the given environmental phase that have a visibility of that location.

A total viewshed was derived from each separate cumulative viewshed where each pixel value greater than 1 was given the value 1 and all pixel values of 0 remain as 0. These total viewsheds represent the landscape areas that are visible from at least one of the active sites for each given cumulative viewshed. The total area of land visible for each of the four phases was calculated as the sum of the area of all pixels that were visible from one or more sites (pixel value > 0).

To understand the distributions of land cover types that were visible from each viewshed, a visibility mask was calculated for each phase. This mask had pixel values of 1 for visible areas and 0 for non-visible areas. The land cover image was multiplied by this mask. Products represent a zero for areas that were not visible and unchanged for areas that were visible. This allowed the area of each land cover type visible to be calculated based on the number of pixels for each class. As the different environmental phases have a different number of sites, directly comparing the area of visibility of each of these land cover types among these phases is not meaningful. To compare the phases, the visibility of each of the land cover classes was calculated as a percentage of the total visibility of that environmental phase. This allows a comparison of the relative distribution of the land cover types among the groups.

This comparison is based only on the total viewshed for each environmental phase and does not account for the instances when multiple sites of the same phase may have overlapping views of the same areas. To understand which land cover classes had repeated representation in areas of overlapping visibility between sites of the same phase, the land cover classification image was first separated into a binary mask for each of the land cover classes where 1 represents pixels with the presence of the class and 0 represents pixels with the absence of this class. These individual images were multiplied by the number of observers (cumulative viewshed value) for each pixel. This was done for each land cover class, and the resulting areas were tallied. These areas now represent the sum of the total area visible for each site including areas which overlap and as a result do not reflect true land surface coverage but instead a measure of land cover visibility preference in site selection.

To understand the local land cover around the sites, a mask was generated by creating a 100 m buffer around each site per phase. This resulted in four sets of 100 m masks for local site adjacency. Areas that were within 100 m of multiple sites of the same phase were merged. The land cover data was clipped by these 100 m buffer masks and four new land cover maps were generated, now only containing values for areas within these zones. As phases with a higher number of sites have more area, these values have been tallied as both the total area of each land cover class as well as a percentage of the total for each phase for useful between-phase comparison.

5.3.4 Statistical Analysis

A statistical analysis was conducted to compare the distributions of the Elevation and Total Area of Visibility among each artistic style (see styles in Table 5.3). Assumption testing was conducted and where parametric assumptions (normality and equal variance) were not met the non-parametric Kruskal-Wallis H test was chosen for this comparison (Singh et al. 2013). No statistical comparison was made of the environmental phase groups as these do not reflect individual samples and many data points are shared among groups, for example, NRFs inclusion in both Sea Level Rise and Transgressive phases.

The relationship between visibility and elevation was explored by calculating a correlation coefficient (R) and conducting a linear regression for all sites. This was conducted to understand how much the differences in visibility are explained by patterns within elevation levels of the sites.

5.4 Results

5.4.1 Rock Art Sites

In total 103 rock art sites were identified in the study area. Of these sites, 25 show art styles associated with the post-glacial Sea Level Rise Phase, 30 with the marine Transgressive phase, 72 with the Big Swamp phase, and 47 with the Freshwater phase. While only 103 sites were identified, some of these sites showed styles from multiple phases and so have been included in both phase counts accordingly (hence n > 103). Table 5.4 shows the duration of each phase in years along with the number of sites associated with each phase and the number of sites per 1000 years.

Table 5.4 Number of sites associated with a phase given as a total and per 1000 years

Phase	Phase Duration (years)	Number of Sites	Number of Sites per 1000 years
Sea Level Rise	6000	25	4
Transgression Phase	1500	30	20
Big Swamp	2400	72	30
Fresh Water	4400	47	11

Figure 5.4 shows the number of sites that contained motifs of each given style but does not represent the number of motifs at any given site. Figure 5.5 displays the distribution of these sites throughout the landscape for each phase.

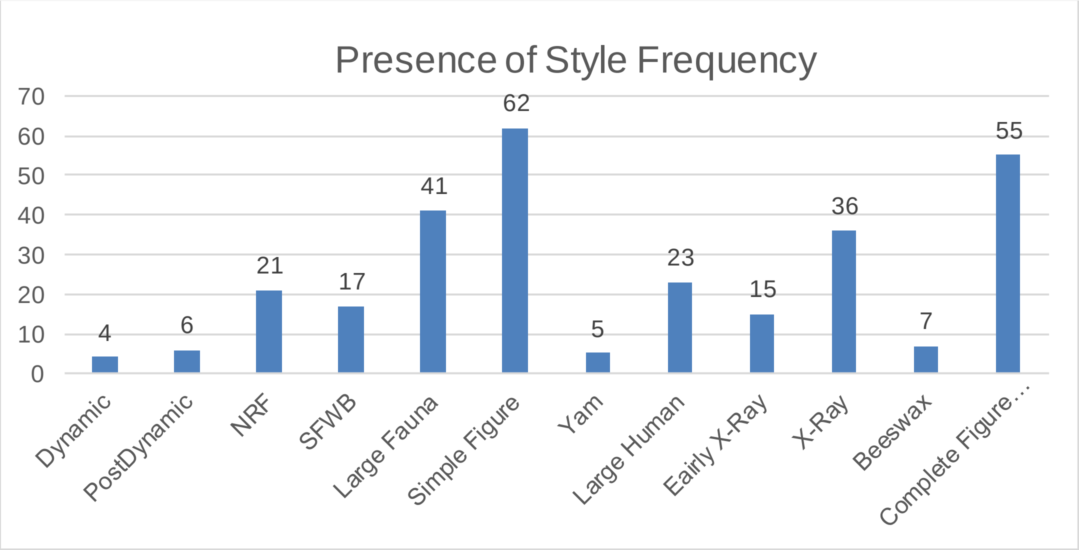
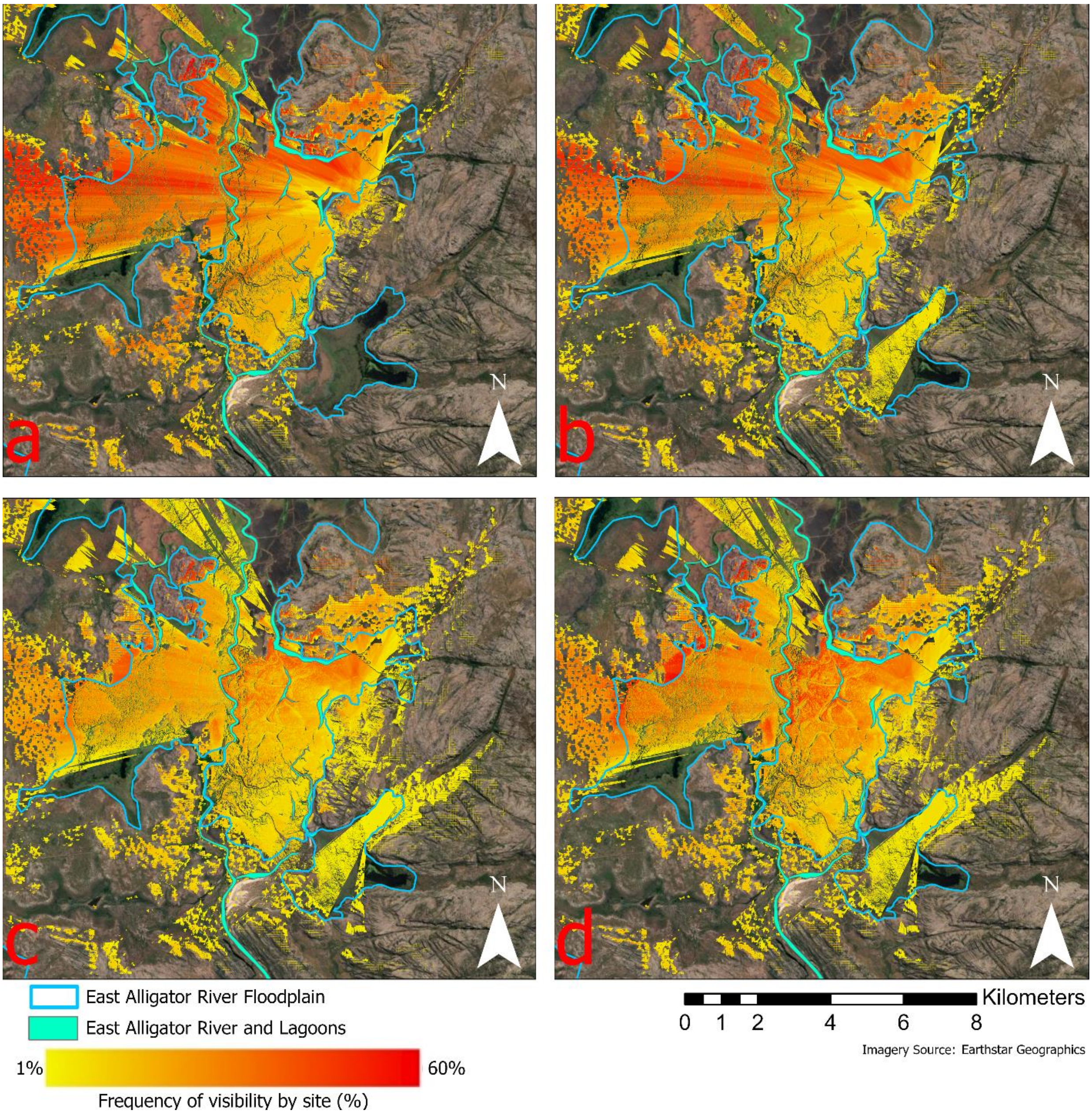


Figure 5.4 The frequency of sites with given artistic style present

Figure 5.5 Site placement density by environmental phase: a Sea Level Rise phase, b Transgression phase, c Big Swamp phase, d Freshwater phase

5.4.2 Visibility Analysis

Figure 5.6 shows the cumulative viewshed analysis from the rock art sites for the entire study area per phase. The viewsheds have been separated into the four environmental phases: Sea Level Rise, Transgression, Big Swamp, and Freshwater phases, represented by A through D respectively. The number of different sites of a given phase that share a view of an area of land surface are given as a percentage per phase to allow comparison among the phases despite an unequal number of sites per phase. The percentages are calculated per phase, so a pixel with a percentage of 60 (represented in red colour in Figure 5.6) is located on an area of land surface visible from 60 percent of the sites that were active during that phase. The figure shows that during the Sea Level Rise and Transgression phases most sites had views of the landscape that covered very long distances. These were focused views with many of the sites active during these phases having overlapping views of the same specific distant area of land surface. The figures show that during the Big Swamp and Freshwater phases, visibility was more focused on the floodplain areas particularly to the east of the East Alligator River.



Imagery Source: Earthstar Geographics

Figure 5.6 Areas visible from sites and frequency of site visibility (%) by environmental phase: a Sea Level Rise phase, b Transgression phase, c Big Swamp phase, d Freshwater phase

5.4.3 Statistical Analysis

Table 5.55 shows the mean and standard deviation (SD) for the elevation (m Australian Height Datum [AHD]) and area of land surface visibility (km^2) for each group. Figs. 5 and 6 show the elevation and visibility by phase respectively.

Table 5.5 Mean site visibility and elevation by environmental phase. SD; standard deviation. AHD; Australian Height Datum

Phase	Visibility (SD) km²	Elevation (SD) m(AHD)
Sea Level Rise	9.20 (7.5)	50.53(14.10)
Transgressive	7.74 (7.18)	45.47 (17.43)
Big Swamp	5.75 (6.67)	35.86 (21.44)
Freshwater	7.07 (7.34)	34.91 (22.70)

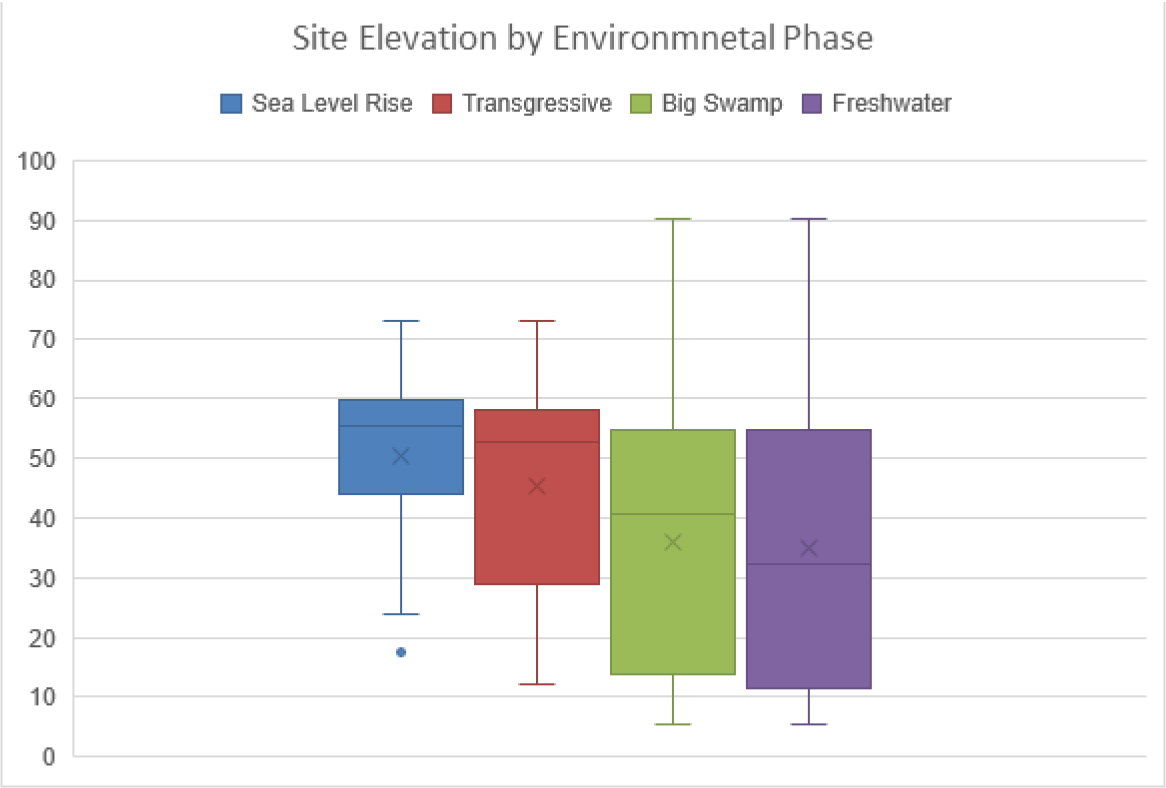


Figure 5.7 Box plot of site elevation (m Australian Height Datum [AHD]) for each environmental phase. x represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range).

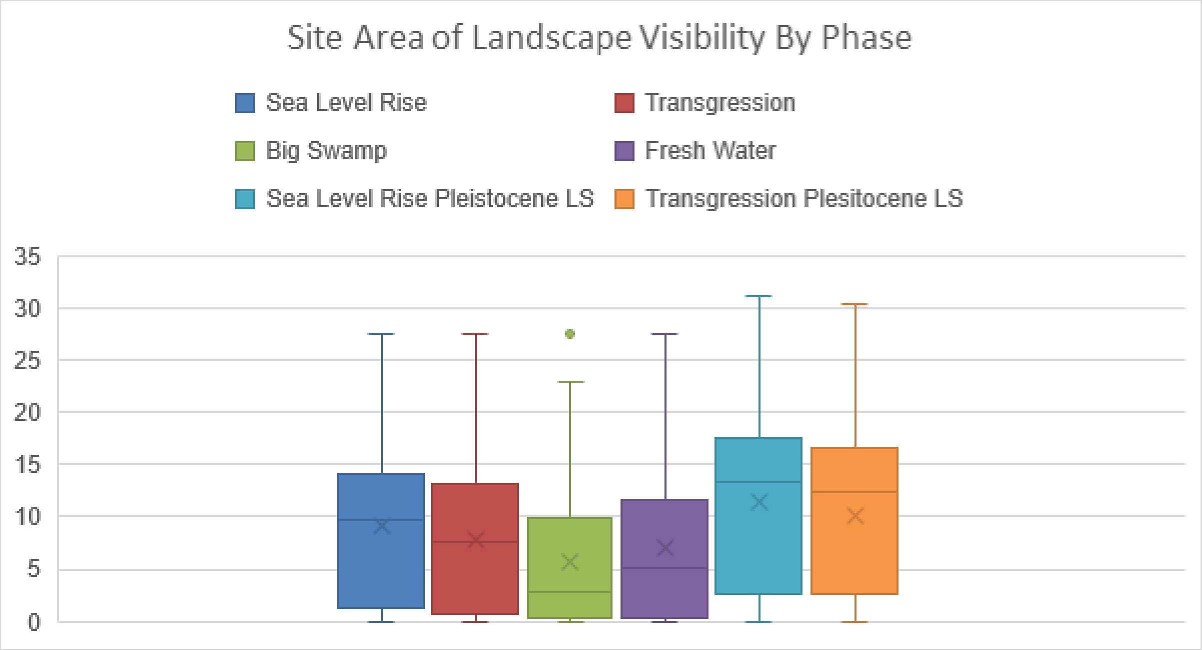


Figure 5.8 Box plot of site land surface visibility (km²) by environmental phase. x represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range). Sea Level Rise Pleistocene LS and Transgression Pleistocene LS show the area of landscape visibility using the digital elevation model derived from subsurface features which may better represent the Pleistocene land surface contemporary to these phases.

The correlation between land surface visibility and site elevation is weakly positive (R = 0.38). The R^2 of 0.1448, shows that only 14% of the variation in visibility is explained by elevation. Figure 5.9 and 5.10 demonstrate the distribution of site elevation and total area of visibility, respectively, by artistic style presence.

All elevation groups violated parametric assumptions of both normality and equality of variance. The Kruskal-Wallis Test found that the distributions of site elevations were significantly different among the artistic styles, $H(11) = 20.544$, $p = 0.038$. The pairwise comparison of groups conducted as part of the Kruskal-Wallis Test found significant differences among the NRF style and Dynamic figures, Post Dynamic figures, Simple figures, Large Fauna, Large Human figures, Beeswax figures, Early X-ray figures, X-ray figures and Complete Figure Complex. No significant differences were shown between any other style pairs indicating only the NRF has a significant difference in elevation distribution among the styles.

The Kruskal-Wallis Test found that the distributions of site total visibility areas were not significantly different among the artistic styles.

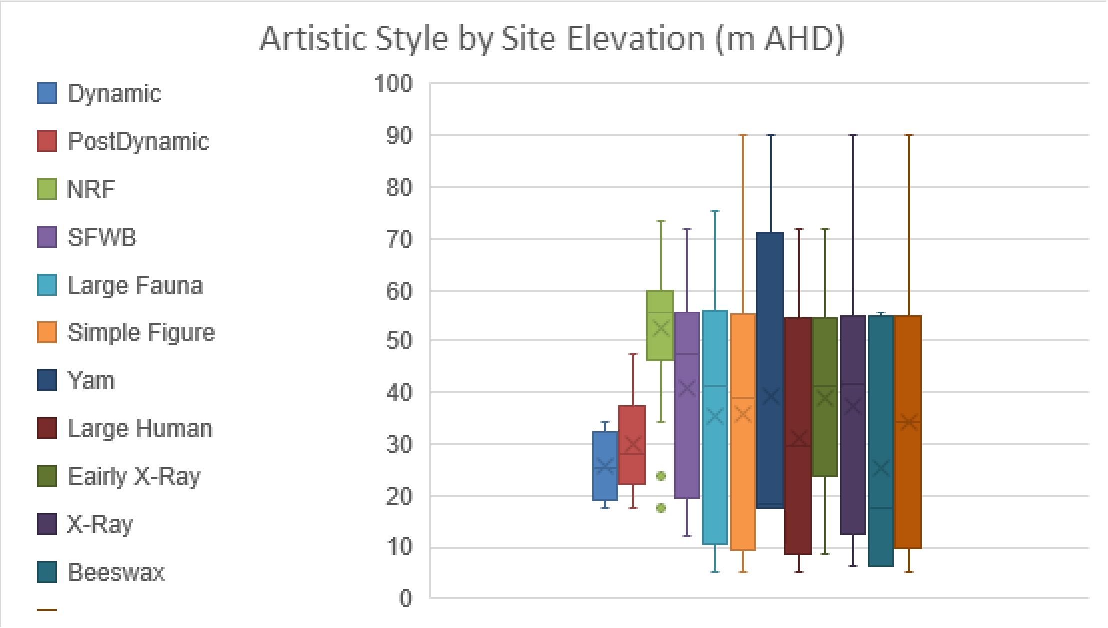


Figure 5.9 Box plot of artistic style by site elevation (m Australian Height Datum [AHD]). x represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range).

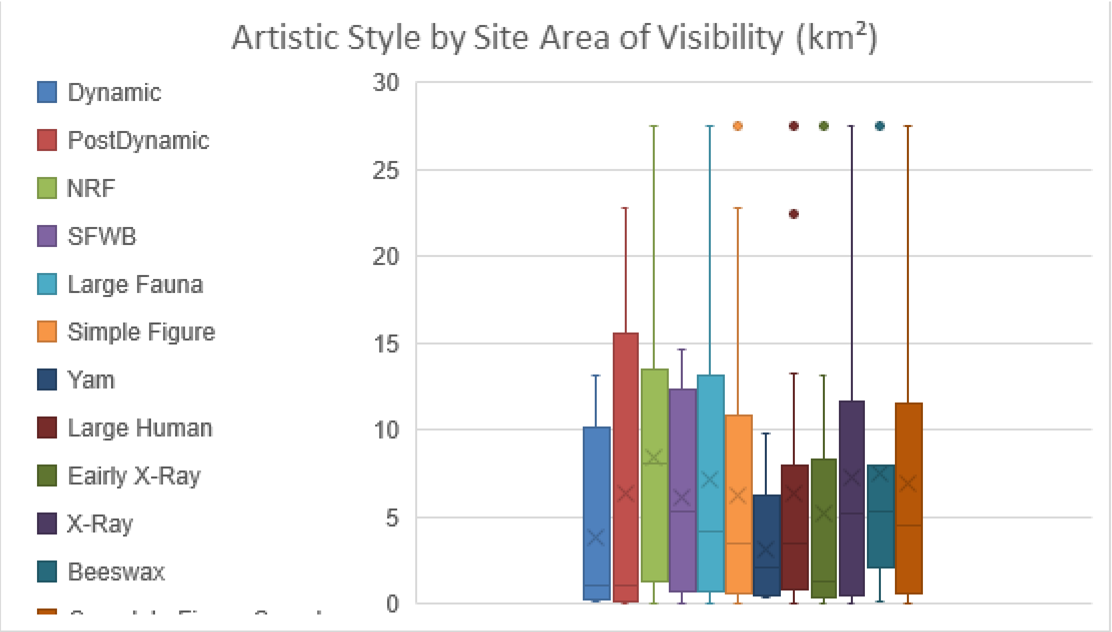


Figure 5.10 Artistic style by site area of visibility (km^2). x represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range).

5.4.4 Greater Red Lily Lagoon Area Land Cover Mapping and Analysis

Figure 5.11 shows the map of the land cover classes produced for the full study area, which covers the extents of the visibility analysis.

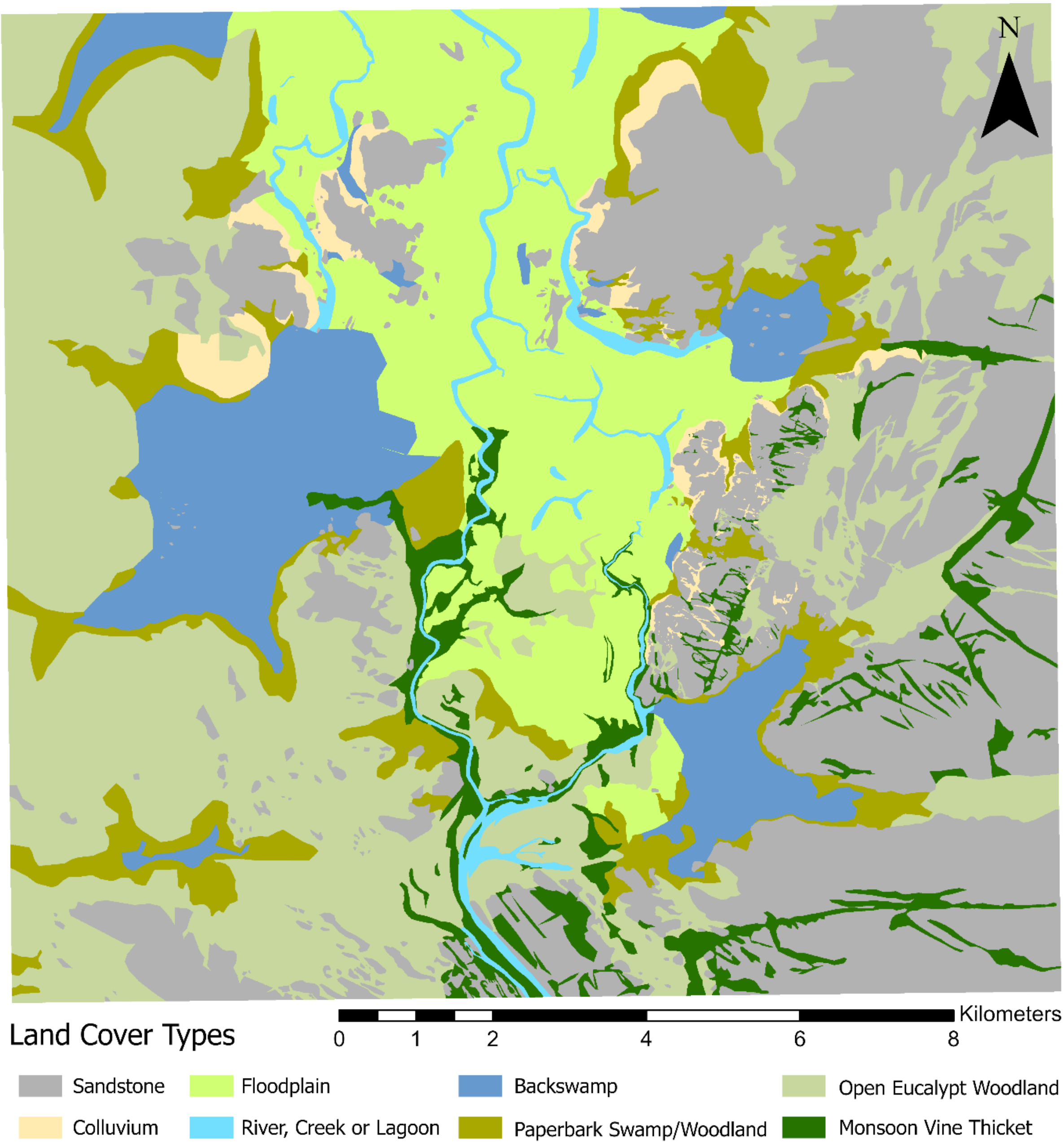


Figure 5.11 Land cover map of the study area today. The boundaries of this map represent the extent of the visibility analysis.

The total area of land cover type visibility is reflective of site frequency (i.e., phases with more sites will have a higher total area visible which may be only due to site preservation) and cannot be directly compared without converting to a percentage of total visibility for each phase. Table 5.6 shows these values as a percentage of the total visible land surface for each environmental period allowing comparison to each other.

Table 5.7 shows the area of land cover class visible from each site within an environmental group summed together (cumulative viewshed). This means multiple sites looking at the same area will count that area cumulatively once for each site. This table is again given as a percentage of the total cumulative visibility per phase for comparison.

Figure 5.12 and Figure 5.13 show the results from Tables 5.5 and 5.6 respectively.

Table 5.6 Land cover class visibility as a percentage of the total visible land surface by environmental phase

	Backswamp %	Colluvium %	Sandstone %	Creeks %	Floodplain %	Monsoon Vine Thicket %	Open Woodland %	Paperbark Swamp %
Sea Level Rise	17.25	1.85	12.70	1.94	35.35	2.91	22.18	5.81
Transgression	19.07	1.75	12.84	1.78	33.18	2.89	21.58	6.92
Big Swamp	16.60	1.76	15.74	1.87	30.67	3.31	22.75	7.31
Freshwater	17.12	1.76	15.39	1.90	31.51	3.24	21.73	7.34

Table 5.7 Cumulative land cover class visibility by environmental phase

	Backswamp %	Colluvium %	Sandstone %	Creeks %	Floodplain %	Monsoon Vine Thicket %	Open Woodland %	Paperbark Swamp %
Sea Level Rise	21.89	2.34	11.60	1.88	33.79	0.08	18.62	5.17
Transgression	22.16	2.51	12.20	2.00	34.55	0.12	17.33	5.31
Big Swamp	20.38	2.61	13.76	1.98	34.38	0.22	16.19	5.58
Freshwater	20.26	2.67	12.48	1.89	35.76	0.24	15.92	5.65

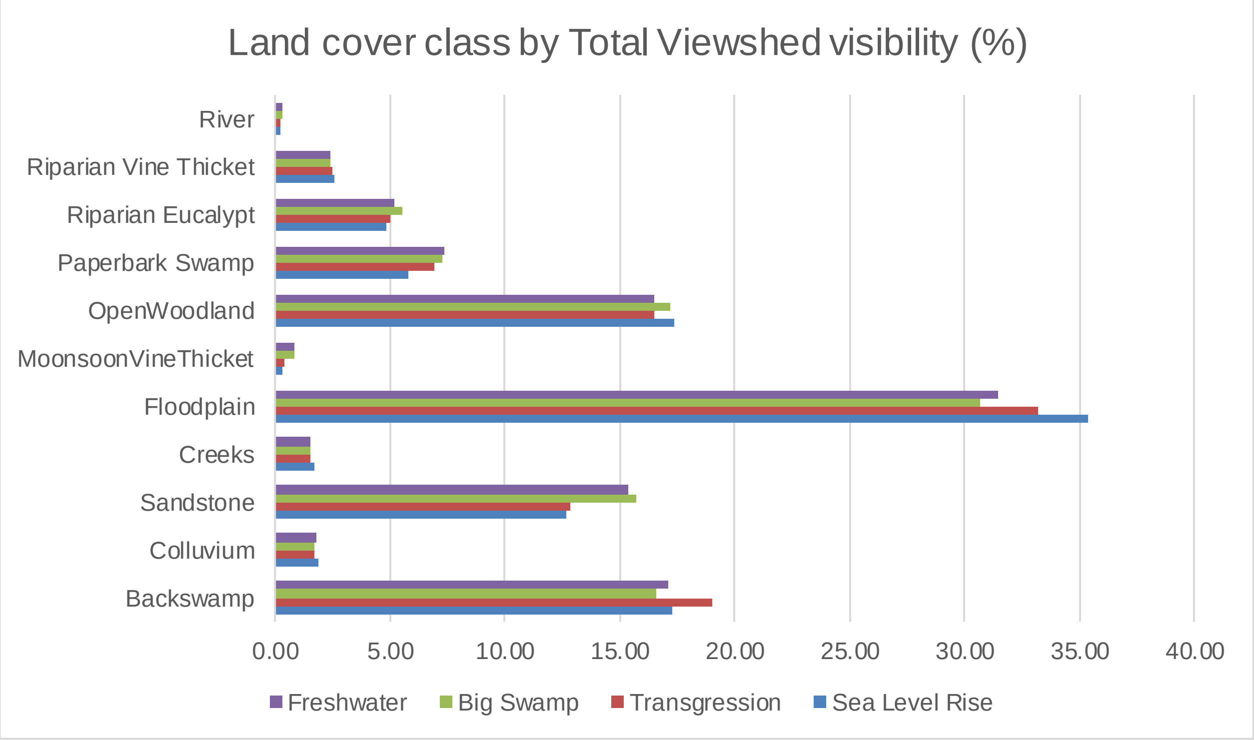


Figure 5.12 Land cover class by total viewshed visibility as a percentage of environmental phase total visibility

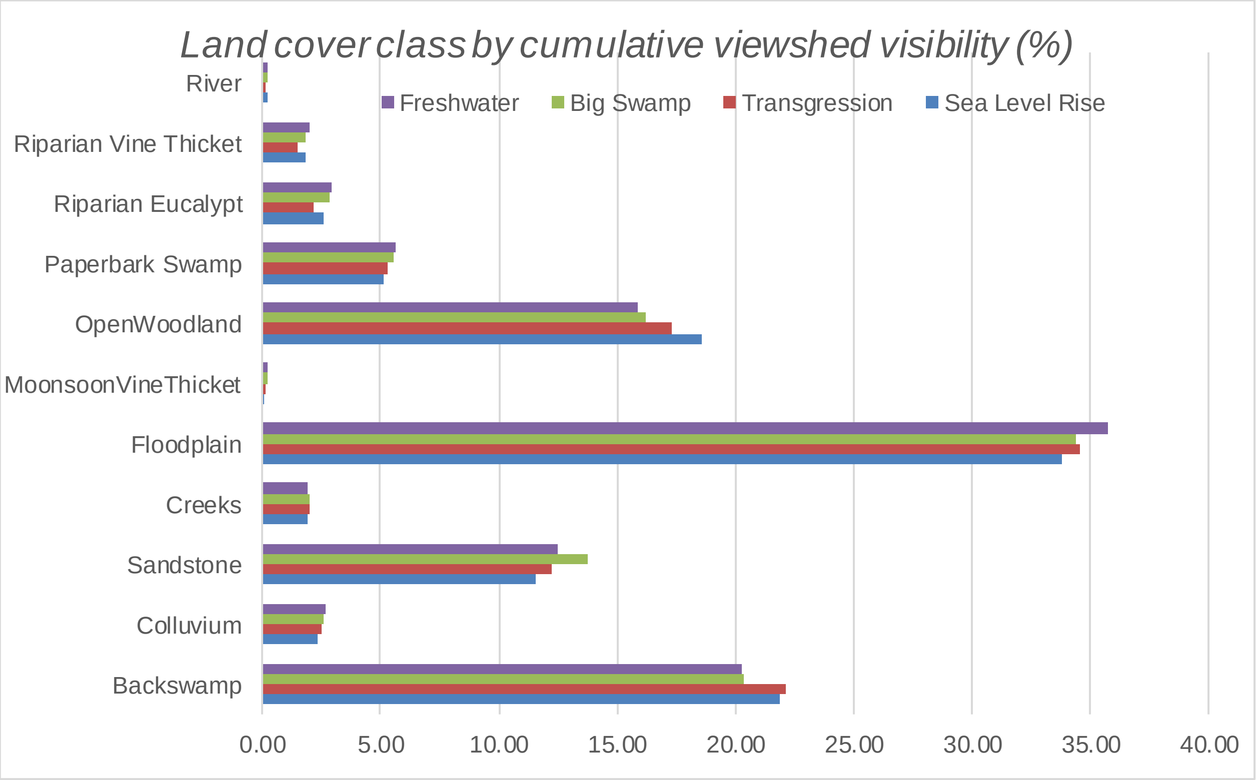


Figure 5.13 Land cover class by cumulative viewshed visibility as a percentage of environmental phase total visibility

Table 5.88 shows the area of each land cover class that occurred within 100 m of a site as a percentage of the total area within 100 m of sites for each environmental period. Areas within 100 m of two sites are joined. The total area is reflective of the total 100 m area around each site and shows a larger area for a period with a higher frequency of sites as well as sites that are less clustered and have more than 100 m spacing between sites. Table 5.8 shows these results as a percentage of the total area within 100 m of sites for each environmental period. Figure 5.14 displays these results.

Table 5.8 Land cover class area within 100 m of rock art sites as a percentage of total area, by Environmental Period

	Backswamp %	Colluvium %	Sandstone %	Creeks %	Floodplain %	Monsoon Vine Thicket %	Open Woodland %	Paperbark Swamp %
Sea Level Rise	0	6	79	1	1	10	2	1
Transgression	0	6	78	1	0	9	3	4
Big Swamp	0	8	70	2	4	6	3	8
Freshwater	0	29	0	8	14	20	8	21

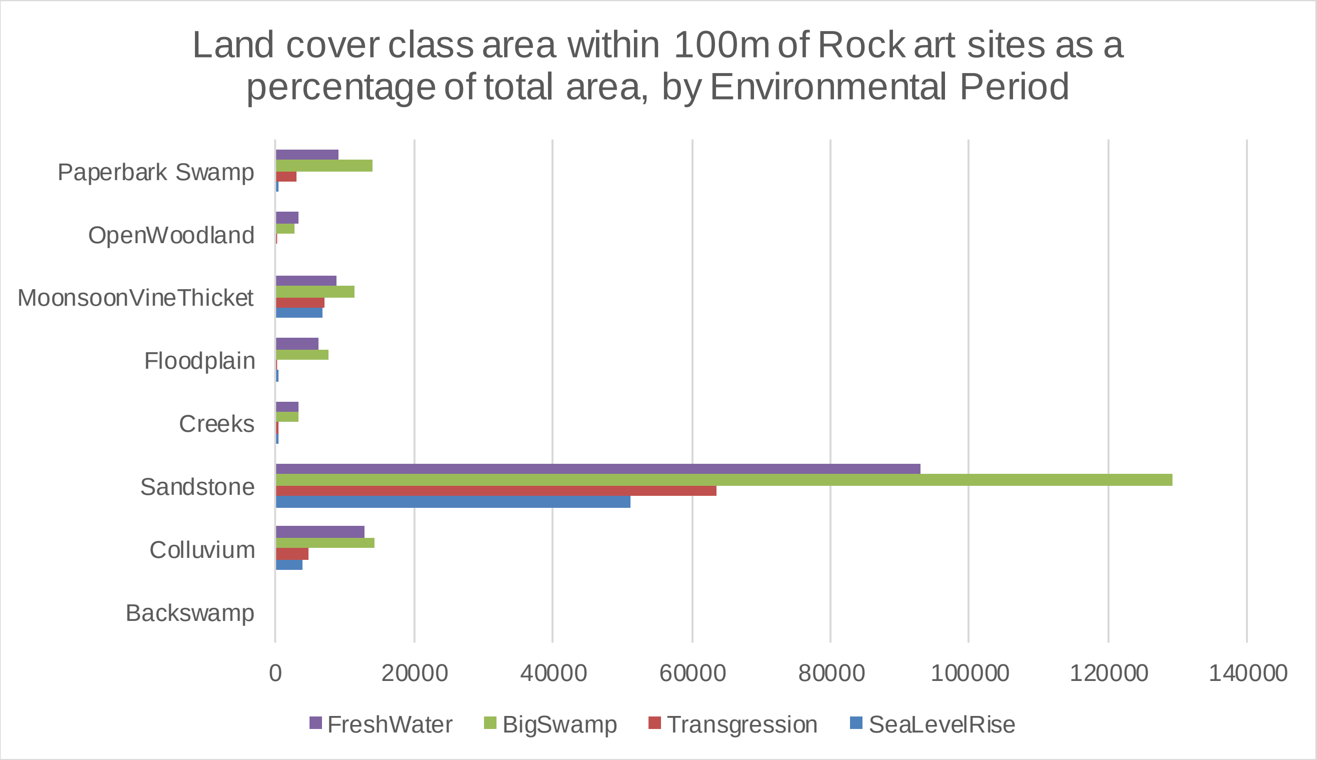


Figure 5.14 Land cover class area within 100 m of rock art sites as a percentage of total area, by Environmental Period

5.5 Discussion

The number of sites per phase is an important indicator of rock art activity at a landscape level. Note that the number of motifs within each site was not considered in this study. For this reason, these values do not necessarily directly indicate differences in the intensity of rock art creation among these periods, as repeated motif generation at a small number of sites may have occurred that will not be captured by these data. Instead, the number of individual sites where rock art was being inscribed demonstrates a pattern of site selection and landscape use during these different environmental phases. The Sea Level Rise phase was found to be the least active phase for new site formation. Despite this phase having the longest duration of the four phases considered, it only accounts for the establishment of four sites per 1000 years, indicating a very sparse use of the landscape during this time. It must be noted that a significant amount of the landscape that was accessible during this time, including sandstone escarpments, is now buried. This is likely to have significant impacts on the number of sites from this phase that are accessible for survey (Kowlessar et al. 2022b) (See chapter four). The Transgressive phase may have been similarly impacted especially in the early periods of this phase. However, the Transgressive phase, the shortest of the four environmental phases considered, had a relative increase in both total number of sites and associated new site development per year, with 20 sites per thousand years. It should be noted that this phase shared several associated styles with the Sea Level Rise phase, however this increase in sites is still noteworthy. This increased use of the landscape, especially the sandstone escarpment, may be associated with the marine transgression and significant loss of land identified in the GRLLA during this phase (Kowlessar et al. 2022b) (See chapter four).The number of sites per phase shows the Big Swamp phase as clearly representing the most active period of rock art site formation. It may be expected that the older sites will be underrepresented due to site preservation and burial during the Transgression and Big Swamp phases. However, the Big Swamp phase is shown to have a larger number of active sites than the more recent Freshwater phase which demonstrates that the frequency of sites during this time is sufficient to overcome taphonomic effects between these two phases.

The increased site frequency during the Big Swamp phase may be explained by the significant change in resources and settlement strategies brought about from the mangroves that filled the floodplains. Excavations in the study area have demonstrated that molluscs were the dominant food source during this phase. The intensification and specialisation in mangrove molluscs have also been associated with increased periods of site usage and population growth (Brockwell et al. 2011; Shine et al. 2016; Shine et al. 2015; Shine et al. 2013; Wesley et al. 2017: 47; Woo 2020). This increase in site development may relate to the major change in resources available in the Big Swamp phase’s flourishing mangrove colonies compared to the previously open woodland environments. Shellfish resources may explain the shift away from flexible foraging strategies towards more reliable sedentary foraging. The timing of this increase in site development coincides with a proliferation of artistic styles thought to be associated with changes to social structures, systems and boundaries emerging from the transgression (Lewis 1988; Morwood and Hobbs 1995; Taçon and Brockwell 1995). This change in landscape use shows that the spatial context of artistic inscription practices changes along with the artistic styles of depictions during this time.

The number of rock art sites on the plateau increased during the Big Swamp phase (see Figure 5.5). The Big Swamp phase has the widest geographic use of the sandstone plateau, and the Freshwater phase consolidates use but maintains a broad distribution. This increased usage of sandstone plateau is also reflected in the increased sandstone adjacency within 100 m of sites during these later phases (see Figure 5.14). These results support an interpretation of the mobility changes during the flourishing mangrove forests of the Big Swamp phase, encouraging greater residential mobility to occur on the escarpments and out of the mangal forests below (Allen and Barton 1989; Hiscock 1999). This contrasts with the previous phases where escarpment edges close to the area of the modern-day floodplains would have been more easily occupied with open woodland savanna and riparian corridors during Sea Level Rise and Transgressive phases.

The statistical tests which compared elevation levels of sites by phases (Figure 5.7) showed a significant difference between the elevations distributions of these phases, suggesting that sites of higher elevation were preferentially selected during Sea Level Rise and Transgression phases. The pairwise comparison of groups shows that the elevation distribution of the NRF style was the only group that was statistically different from the other style's elevation distributions. The pairwise comparison indicates that the differences between the elevation ranges of the four phases was entirely reliant on the NRF distribution's presence in the Sea Level Rise and Transgression phase and its absence from the Big Swamp and Freshwater phase. This suggests that the preferential selection of higher elevation sites during the Sea Level Rise and Transgression phases may only apply to the NRF style. The other styles of the Sea Level Rise and Transgressive phases were not found to favour high elevation locations in this same way. The strong site selection preference for high elevation sites attributed to NRF style found in this study further supports previous research which reported a preference for NRF sites being located on escarpment tops (Wesley et al. 2017; Jones and May 2017). These results demonstrate that the pattern of elevation is unlikely to be the result of better preservations of high up sites, as the other artistic styles of the Sea Level Rise and Transgressive phases do not show similar elevation ranges to the NRF's.

When we consider the total area of visibility calculated using the pre-transgressive elevation model for the Sea Level Rise and Transgressive phases (see Figure 5.8, Sea Level Rise Pleistocene LS and Transgressive Pleistocene LS), this increase in visibility is significantly higher. Whilst this elevation model is highly generalised for the study area, it captures a model of the lowlands which underlies the contemporary floodplain. All morphological models of this region show that these areas were between 15 and 7 m lower than the contemporary surface elevation all the way across the floodplain (Kowlessar et al. 2022b; Wasson 1992; Woodroffe et al. 1989; Woodroffe et al. 1985). This relationship is difficult to explore further without more detailed models of the pre-transgressive land surface and associated land cover units for these areas. However, the results of the visibility analysis do indicate that the areas calculated for these earlier phases using the contemporary elevation model underestimate the total area of land surface visible at the time of the rock art inscription.

Elevation (AHD) and total area of visibility show little to no correlation. This indicates that sites being selected for their elevation may not be chosen to maximise the general view but may instead indicate a preference for specific views providing visibility of specific areas or landscape features.

When the cumulative viewshed is considered, two very distinct patterns of visibility preference can be observed. Long-distance, north-facing views are associated with the Sea Level Rise and Transgressive phases, followed by views focused on the nearby floodplains on the east side of East Alligator River during the Big Swamp and Freshwater phases (see Figure 5.6). This may be interpretable within the context of the changing environments during this time. If the model of human displacement associated with the post-glacial sea-level rise is to be followed, especially with river corridors as the major path, the GRLLA represents a significant location at the extent of the transgressive reaches along the significant East Alligator River. Coincidentally, the sandstone escarpment on the northern edge of the contemporary floodplains represents a modern-day boundary between clan estates (see Figure 5.2).

During the Sea Level Rise and Transgressive phases, rock art inscription sites seem to have been selected in places where views of very distant landscape features were present. Such landscape features were most commonly the distant stone outcrops to the north, which cross the modern-day clan boundary and occur further seaward along the East Alligator River corridor. This site selection preferences may represent social complexity and possible conflict that has been associated with these phases (Blainey 1975: 90–91; Lewis 1988: 90; Taçon and Brockwell 1995: 121). Following notions of sea-level rise driving inter-group conflict, the defensive advantage of views which cover long distances of the landscape from rock art sites may have played a significant role in the site selection during this time. These views are especially associated with sites where the NRF style was inscribed. Long-distance landscape views may also be associated with more mobile nomadic life ways during the Pleistocene and early Holocene. The large stylistic boundaries that have been observed in the art styles of these earlier periods suggest a much broader landscape use within a single cultural group. Such views make broad use of landscape elements forming a sense of place at an inscription site as well as providing the possibility of additional navigational information and narrative context to associated information exchange. Conversely, more recent interpretations of the inscription of NRFs as part of a ritual behaviour occurring at aggregation sites may also account for this distinct change (Jones and May 2017). This interpretation would place such inscription sites at good meeting zones and places to conduct business with new groups, trade, exchange and develop relationships of reciprocity via these ritual behaviours associated with the inscription of these figures. Choosing high points in the landscape with an extensive view of the East Alligator River, a broad and regionally significant landscape feature, may have played a significant role in the selection of places to conduct these complex ritual behaviours, including the inscription of NRF's.

The period of social complexity and social reorganisation associated with sea level change may have stabilised by the Big Swamp phase where the visibility shifts focus to the closer areas to the east of the East Alligator River, a major mangrove habitat at this time (Kowlessar et al. 2022b). Hunting strategies may have also played a role in these changes in visibility focus, with vertebrates including macropods representing significant portions of the diet during the earlier phases, and a shift to mangrove resources during the Big Swamp phase. This is especially true for the Freshwater phase where even more intensive focus on the directly adjacent floodplain can be seen in the cumulative viewshed. During this period, floodplain and associated wetland resources such as fish and birds played a major role in subsistence strategies (Allen 1989; Chaloupka 1993; Clarkson et al. 2017; Clarkson et al. 2015; Schrire 1982; Shine et al. 2016; Shine et al. 2015; Shine et al. 2013; Wesley et al. 2017; Woo 2020).

Changes in the land cover class visibility, when considered as a percentage of the total visibility for each phase, allows further characterisation of the changing preference in view during these periods. Open woodland shows a higher visibility preference within the older phases. As this is based on contemporary open woodland this needs to be considered in association with the floodplains which are thought to have also been open woodlands during the older phases. This preference of view may reflect the resource availability associated with these areas, with vertebrates more present in older diets (Allen and Barton 1989; Clarkson et al. 2017; Clarkson et al. 2015; Schrire 1982; Woo 2020). Such a visibility preference may not be purely utilitarian as a strategy for spotting animals, but may instead be associated with stories and teaching associated with hunting. This is especially significant when the context of art as a communication medium is considered. Similarly, this strongly indicates that the significance of spatial context and sense of place contribute to the function of rock art as a medium of information exchange. Further, stylistic analysis of hunting and animal depictions may provide further insights into this visibility preference.

Similarly to open woodland, backswamps have higher visibility within the older phases. During these phases, backswamps were likely to be exposed sandstone escarpments and open woodland (Kowlessar et al. 2022b). Floodplain visibility preference is greatest for the Freshwater phase, which again correlates to the period during which this was likely to be the area of the most significant resources. By further characterising not just the styles and their spatial distributions but also their unique relationships to landscape perception, these results may further support modelling for site prospection in this important rock art province.

5.6 Conclusion

When the distribution of rock art sites within the GRLLA is considered in the context of the chronology of their artistic styles and the dramatically contrasting environmental phases of the region, some clear patterns of site selection and settlement strategy can be observed. This shows a trend from a period of changing social complexity, where high elevations were preferred with tactical views of clan boundaries in the landscape, to a more resource-focused distribution of site placement during the late Holocene. Through the use of spatial analysis, the impacts of the dramatic transgressive flooding and subsequent mangrove development have been demonstrated through the changing use of the sandstone escarpment representing changes to human mobility and relative population density associated with this loss of land. In this way, a more complete understanding and interpretation of rock art has been demonstrated to benefit significantly by the addition of geomorphology and environmental history data, to best understand the nuanced patterns observable within this assemblage.

5.7 Acknowledgments

Jarrad Kowlessar is the recipient of a Flinders University Postgraduate Scholarship. Ian Moffat, Tristen Jones and Daryl Wesley were all supported by George Chaloupka Fellowships from the Museum and Art Gallery of the Northern Territory. Daryl Wesley is the recipient of an Australian Research Council Discovery Early Career award (project number DE170101447) funded by the Australian Government. Ian Moffat is the recipient of an Australian Research Council Discovery Early Career award (project number DE160100703) funded by the Australian Government and a Flinders University Early Career Researchers Award. This research was approved by Northern Land Council permit #79130 and via Flinders Human Research Ethics application #7704. Thank you to the Njanjma Rangers who provided outstanding support for the research.

CHAPTER SIX

Chapter 6: An immersive perspective: A data driven approach to virtual cultural landscape simulation using Unreal Engine 5.

6.1 Introduction

Landscape archaeology is burdened by a gap between a data driven archaeological model of a past landscape and the perceived model of that landscape which is generated uniquely in the mind of each person as they engage with such models.

> To perceive the landscape is, therefore, to carry out an act of remembrance, and remembering is not so much a matter of calling up an internal image, stored in the mind, as of engaging perceptually with an environment that is itself pregnant with the past' (Ingold 1993: 152–153).

Phenomenological approaches have attempted to close this gap through direct engagement with the physical space in question, basing archaeological models on this direct engagement. Phenomenology draws attention to the difference between the landscapes that occur in our heads through physical engagement with space, and those that occur in a communicated format external to the actual place, such as a map or other abstracted spatial data (Tilley 1994, 2008, 2010). However, one key difficulty of this approach is that in the case of archaeological landscapes, all information, even that which is gained in the exact geographic locale, is further removed from the place as it was in the past (Chapman and Gearey 2000). This makes archaeological research especially challenging when a high degree of environmental (e.g. climate and vegetation), social (e.g. settlement strategies, land use practices, territorial boundaries and customs), and geographic (e.g. topography, coastlines and sea level) change has occurred since the original deposition of archaeological materials. The archaeological landscapes of the Greater Red Lily Lagoon Study area have experienced significant palaeogeographical change over the extensive history of human activity, from at least 60 ka, precluding a physical phenomenological approach to archaeological analysis of this area.

The challenge, therefore, is to synthesize a multitude of data so as to develop archaeological models of past landscapes and communicate these models in a way that mirrors the practical exploration of place, yet can occur in a digital space. This chapter addresses this challenge using a Virtual Cultural Landscape approach, thereby extending the models of past landscapes previously created in this thesis from separate digital data sources, and combining them into one immersive visualisation, providing a means of meaningful engagement with the past landscapes. This approach aims to leverage the interpretive benefits of phenomenological engagement with space, to better interpret and communicate the combined results derived from the multiple methodological approaches utilised within this thesis.

6.1.1 Virtual Cultural Landscapes and Digital Experience

The term virtual cultural landscape has been used to describe the multitude of highly detailed modern digital data products available to visualize spatial and heritage data (Monteleone et al. 2021). Modern spatial data products allow landscapes to be recorded and represented at multiple scales with highly detailed and visually engaging digital formats (Benjamin et al. 2019; Kowlessar et al. 2019b; Monteleone et al. 2021)(see chapter two). Digital visualisations techniques offer an experiential mode of human engagement with collected data that goes beyond a basic two-dimensional map, but instead allows perceptual intuitions of these represented spaces. This concept of ‘virtual cultural landscapes’ reveals the value of digital visualisations of data beyond simply providing an aesthetic benefit of high detail, to include the conceptual benefits of cognitive engagement. The attraction of more visually appealing or ‘realistic’ graphics from digital products may very well be the human conceptual intuition that more realistic products afford. Interacting with virtual cultural landscapes therefore carries with it a phenomenological process (Johnson 2012: 279). The degree to which this engagement is facilitated is therefore related to the means by which a virtual cultural landscape is represented. For example, a digital map represented in two dimensions on a computer screen offers less intuition of a landscape than a digital map represented by three-dimensional graphics (Kowlessar et al. 2019b). Furthermore, different means of interaction with a virtual cultural landscape are created, which facilitate more immersive intuitive and phenomenological experiences.

Within the area of digital archaeology this has led to the development of highly realistic computer-generated visualizations and simulations of archaeological data (Benjamin et al. 2019; Chandler 2012; Chandler and Clulow 2019, 2020; Chandler et al. 2017; Chandler and Polkinghorne 2016; Chandler 2010; Federal Ministry of Education and Research 2022; Goodwin and Richards-Rissetto 2021; Kowlessar et al. 2019b; Von Schwerin et al. 2016). But beyond just the visual fidelity of these highly realistic visualizations come new means by which these archaeological models of the past can be understood and interacted with.

The MayaArch3D project (https://mayaarch3d.org/en/), begun in 2009, serves as a significant example of a virtual reconstruction approach which has generated a highly engaging virtual cultural landscape visualizing an archaeological model of the past landscape of Copán, a major city of the Mayan civilization and World Heritage Site (Federal Ministry of Education and Research 2022; Goodwin and Richards-Rissetto 2021; Von Schwerin et al. 2016). This project has used LiDAR data to record the landscape of Copán and synthesized this with archaeological models of the past to develop a highly detailed reconstruction of the Mayan city. These highly detailed visualizations were hosted on a publicly accessible Geographic Information System with a web interface to allow interaction and engagement with the archaeological landscape. This project identified the sense of being present in an environment, achieved via a communication medium as a key outcome for archaeological visualizations (Richards-Rissetto et al. 2012). This project ultimately expanded this sense of presence in an environment from visual interactivity to the auditory senses using GIS based 3D modelled sound propagation and acoustics simulation. This was used to allow the sounds of the city, including parades and ritual events to be realistically heard as a user explores different spaces (Goodwin and Richards-Rissetto 2021).

Monash University's 'Virtual Angkor Project' (https://www.virtualangkor.com), begun in 2015, presents another incredible example of a virtual cultural landscape, drawing from a wide assortment of evidence based data to visualize and simulate immersive archaeological models of the city of Angkor in Cambodia in the twelfth century (Chandler and Clulow 2020; Chandler et al. 2017; Chandler and Polkinghorne 2016; Chandler 2010; Monash University 2022). The project uses a combination of computer generated methods to recreate Angkor as a sprawling metropolis during the height of its prosperity, modelling both the city and surrounding regions based on a synthesis of detailed archaeological data and historical sources (Chandler and Polkinghorne 2016). Geophysical and remotely sensed data have contributed to models of road and building configurations of the city, providing the means to visualize data which is otherwise highly abstract from the reality it describes (Chandler and Clulow 2020; Chandler et al. 2017). Importantly, not only is this a reconstruction of the city and surrounding countryside as a place, but also includes thousands of animated humans and animals, representing residents, visitors, and ruling elites from all classes of Angkor population of the time. These digital agents were programmed to move around the city with detailed rules governing their individual behaviour and interactions. These simulations were therefore able to not only visualize the city, but to animate the most currently understood archaeological models of past lifeways there. In this way new insights into the social structure of the time, represented by different classes, professions and other expressions of human activity that may have navigated the streets are presented speaking to both physical and social factors influencing this mobility (Chandler et al. 2017).

Both the MayaArch3D and Virtual Angkor Projects synthesise existing archaeological data and models of the past to create cohesive representations of past landscapes. Such projects demonstrate that virtual cultural landscapes are a highly effective communication medium for both the dissemination of results (which has been a traditional use for visualization) as well as the detailed and experiential exploration of those results (Chandler and Clulow 2019; Goodwin and Richards-Rissetto 2021; Richards-Rissetto et al. 2012). Richards-Rissetto et al. (2012) demonstrates that not only the graphical quality of these simulations is important for communication but also the platform by which these models can be interacted with. The use of virtual reality allows proprioceptive movements to facilitate intuitive engagement with digital cultural landscapes in the same way as a human interacts with a physical landscape (Richards-Rissetto et al. 2012). Virtual reality allows stereoscopic vision and stereo audio experience, via headsets as well as the capacity to be controlled by body movements (moving the head and arms). This means of communication once again adds a new dimension capable of fostering a critical 'telepresence' that may now represent a sort of digital phenomenological experience (Richards-Rissetto et al. 2012). Both projects moved beyond simply representing archaeological models of past landscapes, to simulating elements of those environments that would not otherwise be accessible through traditional archaeological approaches. The MayaArch3D project was used to simulate soundscapes and acoustic patterns whilst the Visual Angkor project simulated social impacts on the way human actors might navigate through the city of Angkor.

It has been argued that the best application of phenomenology is through community engagement as archaeological research facilitates a richer communication of ethnographic perspective and gives critical voice to Indigenous cultural perspective on Indigenous cultural heritage (Monteleone et al. 2021). The use of virtual cultural landscapes for communication and exploration of ethnographic perspectives is a significant departure from the traditional use of visualization for dissemination of archaeological research, which is largely considered a public engagement in the realm of heritage tourism. Instead of the one way dissemination of traditional archaeological uses for visualisations, Monteleone et al. (2021) identify virtual cultural landscapes as being an archaeological communication tool with which to facilitate the sharing between cultural perspectives and archaeological models. In the context of Indigenous Australian Archaeology, where archaeological data must be translated from data to language, and then often be communicated across a secondary language barrier, advancements in communication mediums from archaeologist to Indigenous custodian is of critical importance. Furthermore, the means to open communication and exploration of archaeological data to emic perspectives, communicated through the intuitive, digital, phenomenological medium of digital space holds unquestionable merit and potential, not only for academic and cultural heritage management purposes, but also towards opening new opportunities for meaningful post-colonial dialogues to occur across cultural divides.

In order to contribute to a digital virtual landscape approach which achieves all these important outcomes, this chapter presents a novel landscape reconstruction approach using the Unreal game development engine. The Unreal Engine is a platform designed principally for the development of video games with highly detailed 3D graphics. More recently this engine has expanded specific support for film and video, architectural visualization and a wide range of unique interactivity mediums including virtual reality, mixed reality, augmented reality, and motion capture. All of these products have in common the need to generate visualization of high graphical quality and then facilitate real time interactivity with these simulated environments. To facilitate the rapid prototyping and development of such products, the developers of Unreal Engine (Epic Games) have created an asset marketplace and provided open use access to a massive asset repository called Quixel Megascans. Both of these repositories offer a broad range of 3D assets for free and open use with all Unreal Engine products. Such assets include detailed 3D props including 3D plants, rocks, trees etc., and thousands of surface textures and materials. Furthermore, the Unreal Engine offers a suite of inbuilt assets designed for the accurate simulation of lighting and atmospheric effects which can model lighting conditions under the vast range of earth's atmospheric environments with high realism. All of these features make the freely available Unreal Engine a highly accessible platform for archaeological research. This accessibility is especially advantageous for the development of robust repeatable approaches to Virtual Cultural Landscape development when compared to the purpose-built platforms that have been required for similar projects including MayaArch3D and Virtual Angkor.

Another opportunity of the Unreal Engine is to change the way archaeologists form conceptual models of palaeovegetaion within past landscapes. Within the area of phenomenology and sensory centric approaches to landscape archaeology, the impact of past vegetation patterns has been debated. Due to the uncertainty of the exact placements of individual trees and bushes, the impact that specific vegetation configurations may have had is clearly absent from any model of the past. This uncertainty especially impacts visibility approaches. These approaches have largely focused on terrain and ignored vegetation. However, it is conceivable that any given view may have been at some point in the past obscured by a tree that is no longer present (Chapman and Gearey 2000; Wheatley and Gillings 2000: 5–6). Unreal Engine offers a system of vegetation modelling where individual rules for individual plant and tree species can be generated controlling where they grow. Regardless of the specific species dependent rules provided, this system still has a stochastic component based on a random seed which means that the same landscape can be repeatedly prototyped with different specific placements of vegetation models, yet still placing vegetation in appropriate locations of each given species. This offers the opportunity for archaeologists engaging with these simulations to form generalised relationships with past environments that do not become overly familiar with one specific tree layout.

The approach presented in this chapter makes use of all these features and assets of the Unreal Engine to develop a workflow between ArcGIS Pro and Unreal Engine which generates a data driven interactive model of the late Holocene (Freshwater period), mid Holocene (Big Swamp) and late Pleistocene environments of the GRLLA.

6.2 Methods

6.2.1 Unreal Engine Project, Level Lighting and Atmospheric Simulation Setup

To achieve the aims of this research Unreal Engine version 5.0.3 was used, and the project was created using the blank game template. Firstly, an empty level was created, then to simulate realistic lighting and atmospheric effects appropriate for the area, directional light, sky light, sky atmosphere and exponential height fog objects were added to the level. These are predesigned engine elements designed to simulate a wide range of atmospheric lighting conditions.

A directional light is an illumination source which takes a directional vector to simulate sun sky position, and casts light in this angle. The directional light was set to a ‘sun’ light which allows physical interactions with the atmosphere. The lighting intensity and other default settings were left unchanged. Unreal Engine’s default light matches the sun on a clear sunny day. By enabling ‘sun’ light physical interactions with atmospheric effects such as sun angle driven Rayleigh and Mie Scattering, as well as interactions with cloud volumes, make realistic modifications to the overall lighting intensity. Rayleigh and Mie Scattering describe the scattering of light by particles in the atmosphere and these effects cause the blue appearance of the sky during the day and the colour of sunsets during the evening.

The sky atmosphere is an object which models planetary atmosphere. This can be customized for atmospheric height in km above the ground, earth radius, atmospheric absorption, Rayleigh Scattering and Mie Scattering. All settings remained at default for the Sky Atmosphere. These settings simulate a standardized earth atmosphere, however increased detail can be achieved in the future by customizing the Rayleigh and Mie Scattering scales and absorption amounts to better suit present and past paleoclimate models with regards to humidity and precipitation.

Exponential Height Fog is an engine component which models atmospheric perspective on the ground and between objects in the scene. This is important to add the atmospheric effects, such as Rayleigh Scattering to the landscape, causing realistic faded blue mountains and other important visual indicators of scale. Exponential height fog was added to the scene with a lower default fog intensity of 0.0108. This value was selected based on comparisons to reference photography taken in the field. This value is also a candidate for further fine tuning based on paleoclimate models representing increased dust and humidity. All other exponential height fog settings were retained at default.

Sky light is an Unreal Engine global illumination source which handles indirect light that is reflected from one object to another. This is an important element to fill areas that are shaded from the direct illumination source (directional light) but would still be lit by indirect light. The sky light object captures a spherical map of the level which means that all objects in the scene contribute to the indirect light. This is important to make sure that reflected light is coloured based on the actual scene and is subject to change as that scene is changed. The Sky light was added to the scene with its default values.

6.2.2 DEM to Landscape

Elevation information which describes the land surface of the GRLLA study area has been collected and represented as a Digital Elevation Model (DEM) (see chapters two and five for detailed information on how this data was collected within this thesis). The DEMs generated throughout this thesis to represent the contemporary land surface as well as models of the palaeolandscapes derived from geophysics results are suitable to use as the base terrain structure within the Unreal Engine. In this way, the final product is a highly detailed and immersive hybrid landscape model of the rock art research target area, encompassing all the data collected and assembled in the previous chapters of this thesis. Where chapter two describes the drone capture of the contemporary land surface as a Digital Elevation Model, chapter five describes the generation of a Digital Elevation Model which was derived from this surface, based on the geomorphological modelling described in chapter four. Chapter five also generated a land cover classification of the contemporary land cover units observed in the study area. These datasets were all generated and managed within ArcGIS Pro software.

Unreal Engine allows the import of heightfields to generate 3D terrain within the game engine. This terrain is called a landscape within the Unreal Engine. A heightfield is an image-based dataset and therefore limited to values between 0 and 255. With 16-bit precision (the maximum bit depth Unreal Engine accepts) this value range can include 3 decimal places expanding the range to a possible 65,535 unique elevation values. These values are therefore encoded and not directly representative of real-world elevation. To translate these values from encoded numbers back to real elevation, the minimum and maximum elevation value for the data set must be known. When these values are provided to the Unreal Engine the encoded values can be mapped to this range.

A limitation of Unreal Engine's landscape import process is that the heightfield image is limited to a resolution of 8129 by 8129 pixels which makes a landscape of a large scale very coarse. This can be overcome by dividing the landscape into multiple sections and importing in blocks. However, landscape import can also be handled using the Houdini procedural modelling software package, which can now plug in to the Unreal Engine. To maintain the high-resolution DEM as a single landscape model within Unreal, Houdini's 'HeightField' geometry node was used to generate the Unreal landscapes using the raw 32bit encoded geotiff (.tif) files output from ArcGIS Pro or Metashape. Houdini's nodes can be utilised and exported as a Houdini Digital Asset (HDA) file which can be imported into Unreal and run inside the engine using the Houdini for Unreal Plugin. If a Houdini Digital Asset's display node contains heightfield data, this will be converted into an Unreal landscape when this HDA is used within the engine. Houdini's HeightField Geometry node can take any resolution and scales the entire landscape by the length of the largest axis of the input DEM. Furthermore, this function is capable of handling 32-bit image data extending the possible unique elevation value range to 16,777,215 before resampling to Unreal Engines native 16-bit data format.

DEMs representing the Contemporary (late Holocene) landscape as well as the DEM representing the Pleistocene land surface were imported into the Unreal Engine this way. These two DEMs were both imported into two separate levels with identical atmosphere and lighting setups.

6.2.3 Land Cover Types and Landscape Material Import and Setup

Landscape materials are used to colour and texture landscape terrain models within the Unreal Engine. These materials allow a single landscape model to represent a variety of different land surfaces (for example some areas represent grass and others rock). The landscape material developed for this project was based on the land cover types identified in chapters 4 and 5 which were: Floodplain, Standing water (river, creek, or lagoon), Colluvium, Open Eucalyptus Woodland, Paperbark Swamp, Monsoon Vine Thicket, Back Swamp, and Sandstone. Additionally, Sandstone was divided into three more specific classes: Scree, Acacia Woodland, and Exposed Sandstone.

A separate material function was created to represent the ground surface of each of these land cover types. The material function was built inside Unreal Engine's material editor node-based graph. When creating each material function firstly a representative image of that surface type was chosen (for example a texture of sandstone to represent the exposed sandstone surfaces in the landscape) that will be painted on these surfaces. These material functions have been designed to use physically based rendering (PBR) by including a diffuse texture, a normal map, and a roughness map. A diffuse texture represents a colour image of a surface type which has flat, diffuse lighting. A normal map represents the same image but shows different angles that surface may reflect light representing small geometric components such as bumps and indents without requiring actual 3D geometry. A roughness map represents the same image but shows different areas of smoothness and roughness and controls the ways that light reflects from those surfaces. These three components can be used to make a two-dimensional surface reflect light in the same way it would if it had a three-dimensional geometric structure. Despite replicating the lighting of underlying three-dimensional details this approach is much more computationally efficient than having actual three-dimensional geometry for these small details. These separate material functions were included in a single landscape material function as separate landscape layers.

To correctly map these landscape layers to the geometric landscape unreal allows the use of individual masks for each landscape. These masks were produced using ArcGIS Pro. These classes were encoded in a raster dataset in ArcGIS Pro where discrete pixel values were given a single value representing one of these classes. To export these to the Unreal Engine this dataset needed to be divided into a set of binary masks with only 2 values representing the presence or absence of a given land cover class. This was achieved through the symbology setting in ArcGIS Pro where a select class was given white pixels and all other classes were given black pixels. This raster data set was then exported using the Export Raster geoprocessing function, which was set to use the same clipping geometry used for the DEM exports. The 'use renderer' and 'Force RGB' options were checked to ensure a binary mask output and binary masks were then exported at the 8129 by 8129-pixel resolution which is the maximum size that Unreal Engine can import for landscape material masks. This process was repeated to create one mask that was exported per land cover class.

Before these masks were imported into Unreal Engine, they were edited in with GIMP to apply a 10-pixel gaussian blur. This process breaks up sharp pixelated edges and uses transparency overlays (with weighted blend mode) to allow land cover class to blend in transitional boundary areas once they are imported. Once these masks were applied to the landscape the resolution was scaled to fill the entire extent of the landscape geometry. Because these masks were clipped in ArcGIS Pro by the same clipping extents when scaled in this way, they correctly map to the relevant geographic locations on that landscape geometry.

6.2.4 Landscape Grass Type

Despite the realistic reflections generated by the PBR material the textured landscape is still flat. These materials only represent the ground surface but do not represent rocks, vegetation and other materials upon this surface. For this purpose, Unreal Engine includes Landscape Grass Types. These act as a list of assets (3D geometric models) representing surface foliage and other objects that occur on these surfaces. Within the natural surfaces being modelled by these environments these types of objects include small low growing grasses, shrubs and weeds, small rocks, pebbles, sticks and twigs.

Assets used to represent these objects were acquired from Quixel bridge, and the Unreal Marketplace which both license all assets for open use within the Unreal Engine. Many appropriate plant species for the study area are available in these repositories. In the cases where significant species were absent these assets were generated from scratch using Blender.

A landscape grass type was constructed, with a unique list of assets for each landscape layer and mapped to these layers. For each asset included within a landscape grass type a density can be selected which describes how many instances of this asset will appear within each 10 meters of this landscape layer. Assets and associated densities were selected based on reference images of each of these land cover types captured in the field on site in Arnhem Land.

6.2.5 Procedural Foliage

A limitation of the landscape grass type approach to vegetation modelling is that it can only distribute these vegetation assets evenly over a landscape layer based on each asset’s given density. Whilst this modelling approach is useful to represent consistently occurring groundcover features such as grass and other debris, this does not always realistically model the way that larger vegetation species like trees and larger shrubs are distributed across a landscape (which may cluster together or favour distinct canopy positions within a larger vegetation community). Unreal Engine allows the use of a ‘procedural foliage spawner’ which allows much more complicated rules to control the distribution of individual plant species across the landscape. A procedural foliage spawner is an object that works as a collection of foliage types that will together make a mixed species foliage community. Each individual species can be given a 3D asset to represent this type of foliage and unique rules which impact where it will grow. This procedural foliage spawner can then be implemented within the Unreal Engines level by placing a ‘procedural foliage volume’ which denotes an area within which a given spawner can simulate foliage. The simulation is based on the rules provided for interaction, the underlying terrain (Unreal landscape) over which the volume is placed and a random seed. The seed bales can also be changed in order to restimulate the given vegetation community in the area changing the specific layout of trees to a new layout which still obeys by the same rules. Importantly among the many rules that can be set for these individual foliage types (plant species), landscape layers can be used as inclusion or exclusion layers. This means, for example, Melaleuca Paperbark trees can be limited to only grow on landscape areas that have been masked by the paperbark swamp landscape layers in addition to their other unique placement rules. This allows the vegetation patterns that occur in the final landscape to be paced based on the land cover classification which has been used to mask each landscape layer.

Assets which represent specific plants were selected based on visiting the contemporary landscape and collecting reference photos and a list of major vegetation species. Assets which suitably represented these species were selected from the Unreal Marketplace and Quixel Bridge. If these repositories did not have a suitable model for a key vegetation species this model was instead generated from scratch in Blender using reference photos as a guide. 3D models for *Melaleuca* paperbark and *Rhizophoraceae* mangrove tree species were both generated this way.

6.2.6 3D Photogrammetry Asset Import

Chapter two describes the creation of detailed 3D models of the GRLLA landscape and individual rock shelters. Due to the complex textured surface (fissures, weathering patterns etc.) of the sandstone escarpments of the Kombolgie formation within the study area the heightfield representations of these areas was deemed to be of inadequate resolution to reflect these features. In this case a point cloud classification was performed within Agisoft Metashape and a meshed and textured surface was generated using only those points that were classified as exposed sandstone. This model of the exposed sandstone surface along with each model of rock shelters and rock art painting sites within the landscape were exported as Collada (.DAE) files. These models were imported into Unreal Engine and scaled to 100%. As these models were already correctly scaled through geomatic survey control (detailed in chapter two) these models were correctly sized upon import. These models were manually placed in the landscape in their correct locations.

Figure 6.1 shows the approach to importing the data from ArcGIS and Meta shape used to generate the virtual cultural landscape within Unreal Engine.

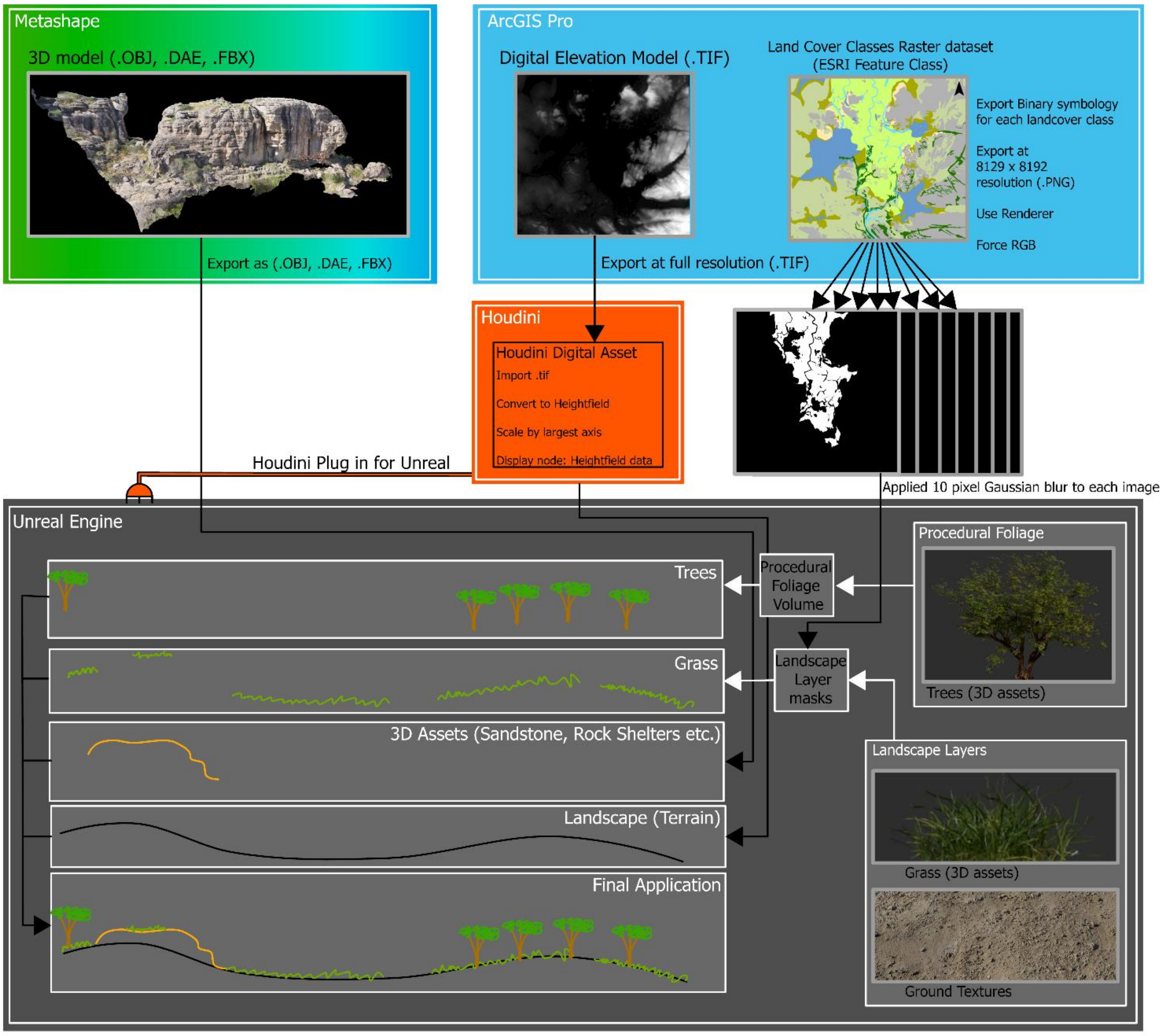


Figure 6.1 Workflow for Spatial data import from ArcGIS Pro and Metashape to Unreal Engine

6.2.7 Palaeolandscape Modelling

Three Landscape models were simulated to represent three key environmental phases of the study area. These phases were: Late Holocene (contemporary freshwater landscape), mid Holocene (Big Swamp) and Late Pleistocene (Pre-transgressive). Each of these landscapes used a different DEM and land cover classification to generate the Unreal landscape and landscape layer masks. Chapter five describes the process of inferring past elevation models by subtracting elevation from the contemporary DEM to various depths based on the underlying geomorphology. The elevation model used in chapter five for the visibility analysis of the Sea Level Rise and Transgression phases was used for the Late Pleistocene elevation model. This was only modified slightly for the mid Holocene elevation model by raising the floodplains to the height of the mangrove sediments at the earliest time that the entire floodplain was flooded (see chapter four).

Chapters 4 and 5 describe underlying geomorphological units and the sequence of environmental events which caused transitions between these units. In this way a land cover classification was derived starting from the contemporary land surface and moving backwards guided by the geomorphology described in chapter four.

Table 6.1 Land cover classification derived from Late Holocene modern land surface for mid Holocene and Late Pleistocene periods

Late Holocene (Modern)	Mid Holocene (Big Swamp)	Pleistocene (Pre-transgressive)
Floodplain	Mangroves	Open Eucalypt Woodland
Monsoon Vine Thicket	Monsoon Vine Thicket	Monsoon Vine Thicket
Colluvium	Sandstone/Scree	Sandstone/Scree
Paperbark Woodland	Colluvium	Sandstone/Scree
Scree	Scree	Scree
Acacia shrubland	Acacia shrubland	Acacia shrubland
Open Eucalypt Woodland	Open Eucalypt Woodland	Acacia shrubland
Backswamp	Backswamp	Sandstone

6.2.8 Interactivity and Visualisation

Several interactivity methods were included in the Unreal Project. Primarily this simulation was designed to be interacted with on a computer screen using keyboard and mouse to fly around the environment. This is the default interactivity method for the Unreal Engine.

Virtual Reality (VR) controls were also added and tested using the Oculus Rift platform. These controls were added using the default predeveloped VR controller assets available within the Unreal Engine. A Navigation Mesh was generated for the entire landscape. This allows a user to enter the simulated environment using a VR platform and move around freely on the land surface and physically collide with landscape geometry, such as cliffs, trees, and rocks.

Real time interaction requires the developed application to be run on a local computer with sufficient hardware in a space setup for a VR platform. These requirements make the simulation restrictive for access. This was deemed an unacceptable accessibility restriction to satisfy the goal of allowing remote Indigenous community access and engagement with virtual cultural landscapes. To increase accessibility to the application and still retain VR perspective, key locations throughout the environment were selected for panoramic capture. Panoramic capture was achieved with the Panoramic Capture Tool plugin which is freely available as part of the Unreal Engine. This tool allows a complete panorama photosphere to be collected from two stereoscopic perspectives. These photospheres can be engaged with on a smartphone phone allowing the phone (with inbuilt accelerometer and gyroscope) to be moved around to investigate any viewing angle from these selected fixed positions. As a stereoscopic result is generated these can also be used within low cost VR headsets designed for use with a smartphone. Figure 6.2 shows an example of a stereoscopic panorama generated from within the Unreal Engine. This output limits perspective to a fixed location and prohibits real time exploration. However, it does allow head movements to investigate the view of the simulation. Importantly this also displays the environment at the real scale from this VR perspective ensuring that views are given the full impact of the real scale environment.

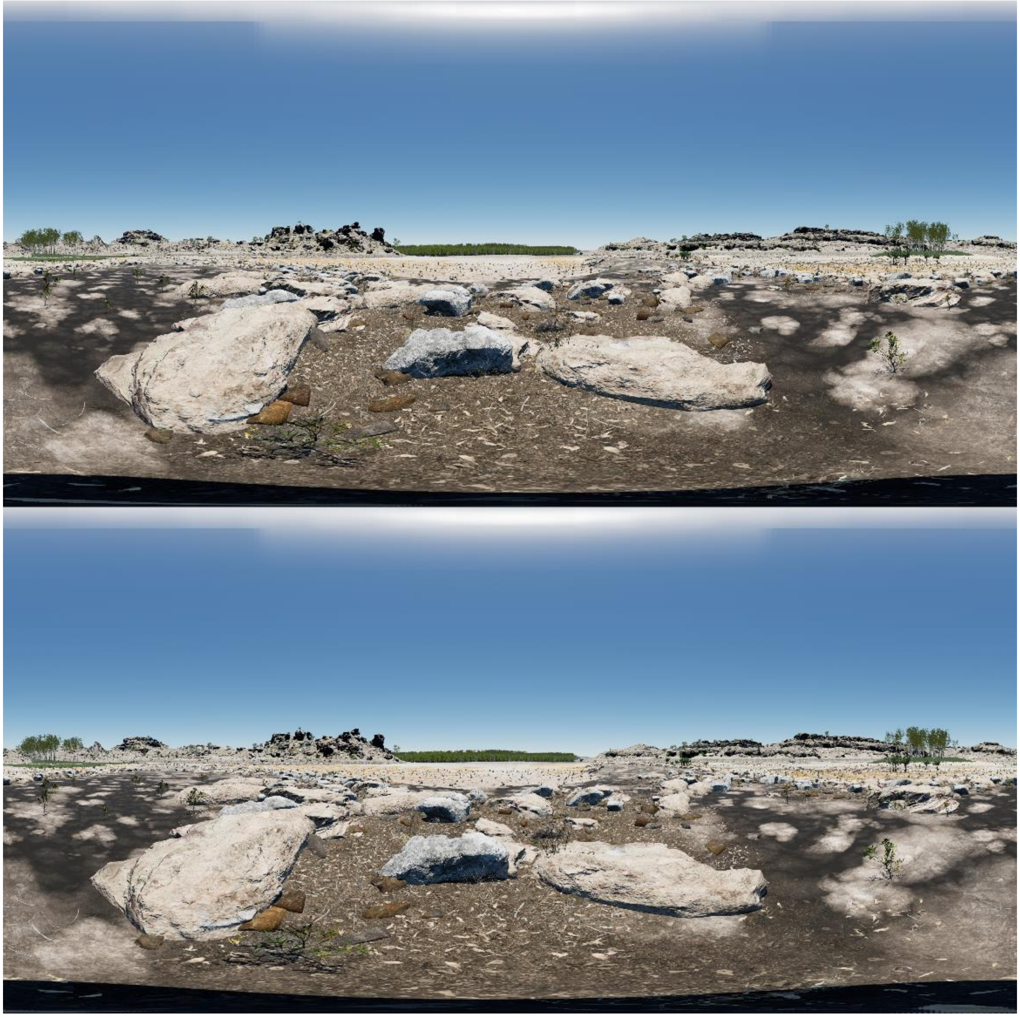


Figure 6.2 Example of a stereoscopic panorama image captured in the Unreal Engine.

6.3 Results

The use of the Unreal Engine to combine the entirety of the collected field data resulted in high-definition, highly realistic, interactive landscape models providing a virtual view back in time to the contemporary landscapes of previous environmental phases, including all aspects of landscape and vegetation changes. Figure 6.3 shows examples of the land cover in Unreal Engine with landscape surface textures, grass layers and procedural foliage. The land cover classes shown are Acacia Shrubland, Mangrove, Backswamps, Lagoons, Monsoon Vine Thicket, Colluvial Aprons, Open Eucalypt Woodland, Freshwater Floodplain, Open Paperbark Woodland/Swamp. These represent land systems of vegetation and underlying geomorphology mapped to the landscape based on the contemporary land cover classification or the derivative land cover maps generated from the models of the past environments presented in chapters four and five.

Figure 6.3 Examples of the land cover types in Unreal Engine with landscape surface textures, grass layers and procedural foliage. The land cover classes shown are A) Acacia Shrubland (on sandstone escarpment), B) Mangrove, C) Backswamps and Lagoons, D) Monsoon Vine Thicket, E) Colluvial aprons, F) Open Eucalypt Woodland, G) Freshwater Floodplain, H) Open Paperbark Woodland/Swamp.

Figures 6.4 and 6.5 each show a single view of the landscape from the landscape simulations of the late Holocene (Freshwater phase), mid Holocene (Big Swamp phase) and the Late Pleistocene (pre-transgression/Sea Level Rise phase).

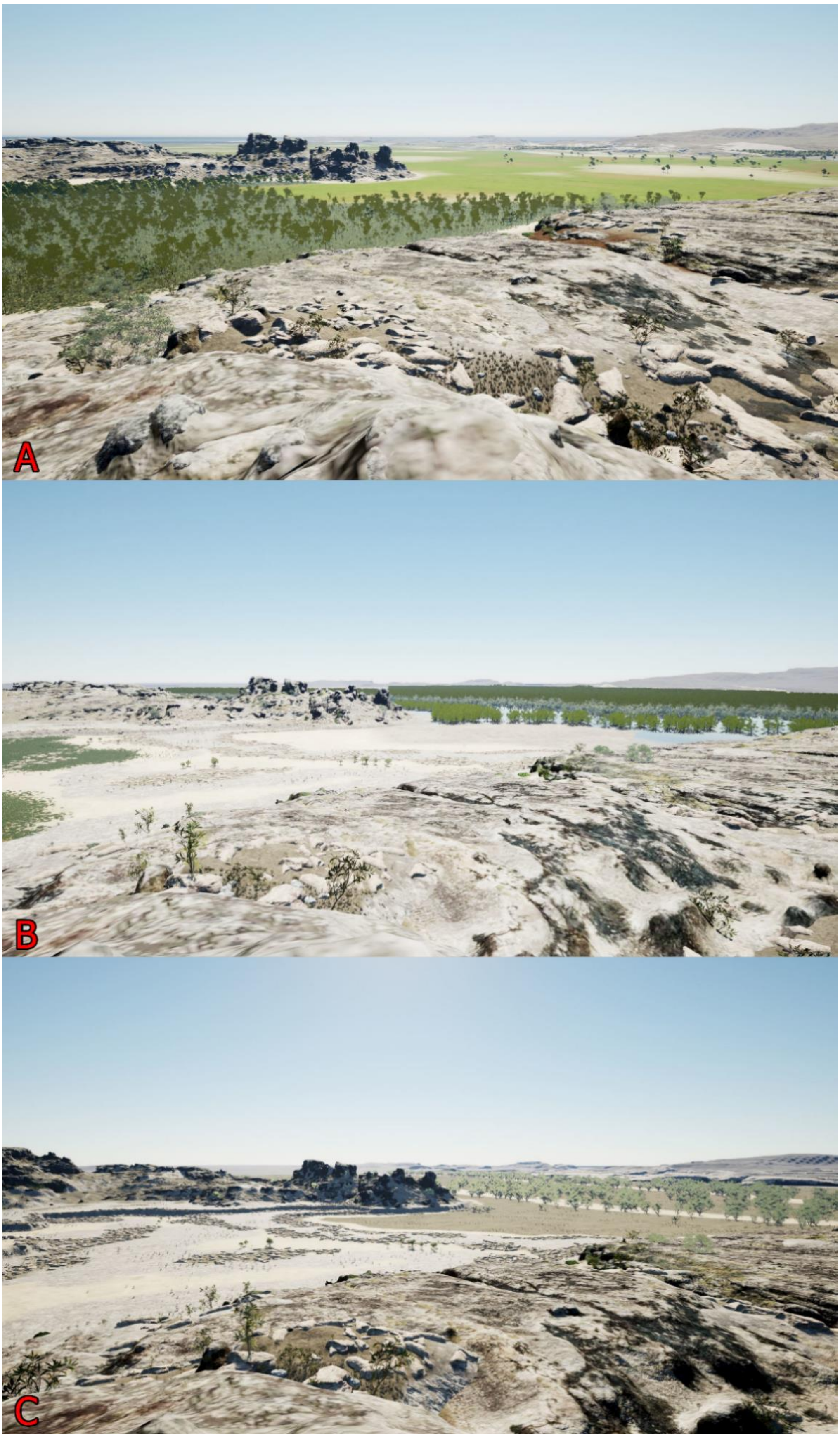


Figure 6.4 Three views from different time periods, high on the sandstone escarpment looking west. A) The Freshwater phase of the Late Holocene, B) The Big Swamp phase of the mid Holocene, C) the Late Pleistocene, before the marine transgression.

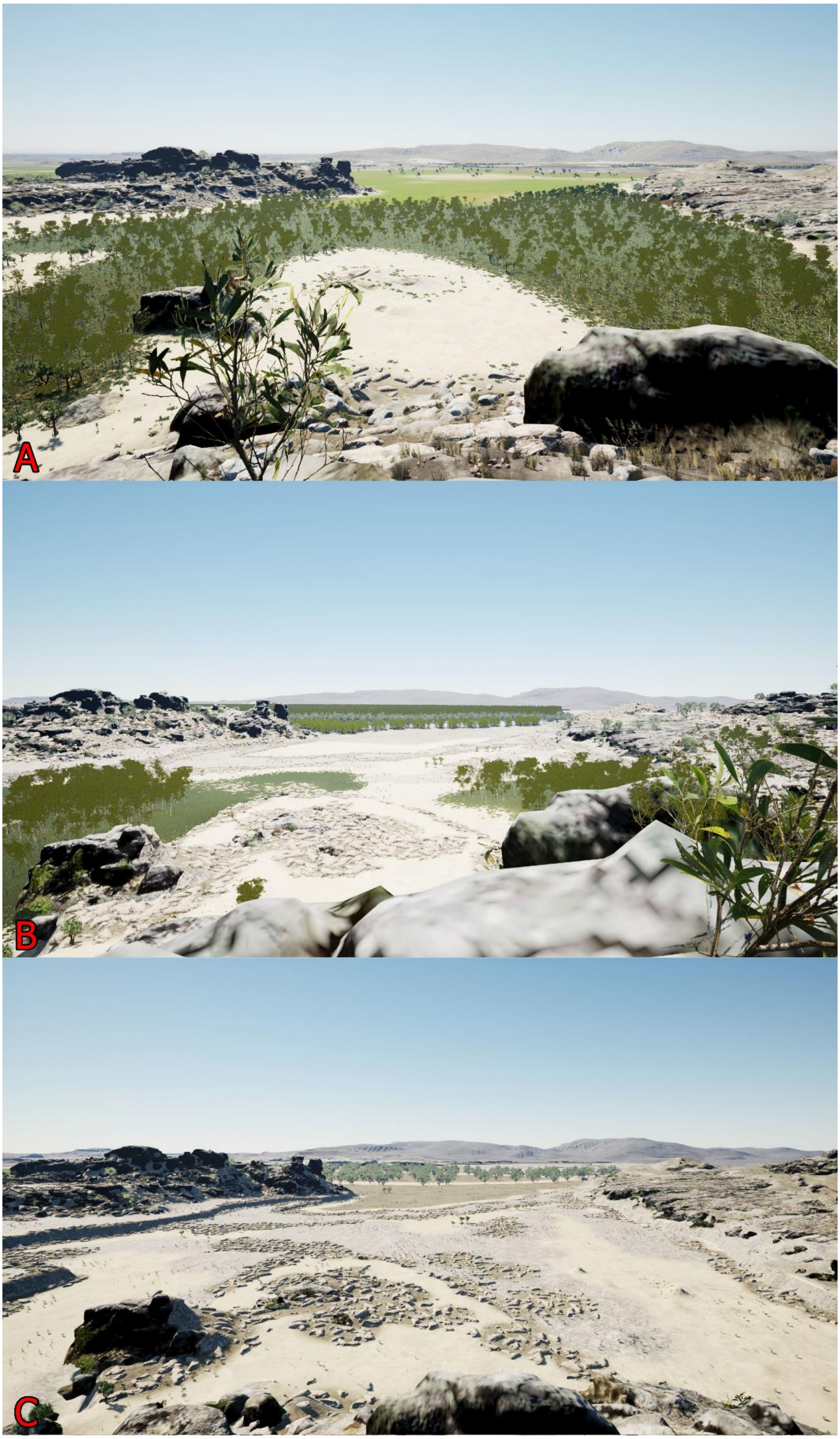


Figure 6.5 Three views from different time periods, high on the sandstone escarpment looking north. A) The Freshwater phase of the Late Holocene, B) The Big Swamp phase of the mid Holocene, C) the Late Pleistocene, before the marine transgression.

The late Pleistocene simulation shows the area of contemporary floodplain, with a lower elevation than the contemporary forest and covered by open Eucalypt woodland and sandy braided creeks (figures 6.4 C and 6.5 C). This view of the Pleistocene shows the sandstone shelf which fills the valley is not completely buried (central to both views in figures 6.4 C and 6.5 C). The mid Holocene simulation shows the areas of the modern-day floodplain filled with marine water and mangrove forests. The pre-existing creek channels became the deepest parts of the flooded surface, supporting flourishing mangrove communities which fill across the valley between sandstone outcrops. In the mid Holocene simulation colluvial fans have buried much of the central sandstone shelf and Paperbark woodland have begun to grow in the valley fringes with the deepest colluvial deposits (central to both views in figures 6.4 B and 6.5 B). In the modern freshwater floodplain (visible in figures 6.4 A and 6.5 A) the contemporary land cover is visible with the freshwater floodplains sitting between 10 and 13 m higher than the underlying Pleistocene landscape (figures 6.5 C and 6.5 C). The central valley is now dominated by colluvial sediments supporting Paperbark woodland.

Figures 6.6 through to 6.12 all show simulated views looking towards the culturally important Seven Spears rock shelter. Figures 6.6 and 6.7 show images from the Late Pleistocene simulated landscape in the Unreal Engine. The escarpment of a now buried sandstone shelf is visible during the Pleistocene, running in front of the Seven Spears rock shelter. These two figures also show the open Eucalypt woodlands present in this area during the Pleistocene.

Figures 6.8, 6.9 and 6.10 show how these same areas looked based on models of the Big Swamp phase of the mid Holocene. This period is set after marine waters transgressed the lowlands of the Pleistocene (seen in figures 6.6 and 6.7) and mangrove species flourished in the now estuarine environment. The sandstone shelf remains visible in these images though partially buried in mangrove sediments.

Figures 6.11 and 6.12 show the same areas but in the Freshwater phase of the late Holocene when this area is the large flat floodplains of the East Alligator River. The sandstone shelf that extended from the Seven Spears rock shelter is now completely buried and invisible in the landscape. Cumuliform clouds can be seen in the atmosphere in figure 6.11 representing an element of the tropical monsoon climate of the late Holocene. The late Holocene landscape model is based on the natural environment and does not include modern post contact features such as the road that runs past the Seven Spears rock shelter in the present day. Therefore, this model might best represent the landscape from 200 years ago. Figure 6.12 has a view towards Seven Spears rock shelter looking over the significant Red Lily Lagoon.

Figure 6.6 A view looking at the Seven Spears rock shelter in the Pleistocene environment.

Figure 6.7 A view of the Seven Spears rock shelter from the open Eucalypt Woodlands that occupied the valleys during the late Pleistocene.

Figure 6.8 A view looking at the Seven Spears rock shelter site during the Big Swamp phase of the mid Holocene

Figure 6.9 A view of the Seven Spears rock shelter from within the mangroves of the Big Swamp phase

Figure 6.10 An aerial view of Seven Spears rock shelter and the front of the sandstone escarpment as it meets the Mangal forests of the Big Swamp phase

Figure 6.11 A view of Seven Spears rock shelter from the late Holocene freshwater floodplains.

Figure 6.12 A view of the Seven Spears rock shelter from Red Lily Lagoon in the late Holocene Freshwater phase.

Figure 6.13 shows a sunset over the late Holocene simulated landscape. The atmospheric effects incorporated into the Unreal Engines lighting can be seen to have highly realistic results.

Figure 6.13 A simulated sunset in the late Holocene landscape simulation. Looking west from the sandstone escarpment.

6.4 Discussion

The approach to virtual cultural landscape simulation presented in this chapter has been designed in conjunction with the larger approach to rock art research presented throughout the thesis. The entire data generated through rock art recording, site modelling, landscape modelling and geophysical analysis have been successfully combined to power the visualisation presented in this chapter. The simulations developed through the Unreal Engine, whilst capable of producing visualisation, also present a real time dynamic environment which can be physically explored and interacted with. These simulations are data driven, ultimately providing a completely new way to interact with these already existing datasets.

The approach is guided by data and generates the visualisations procedurally using this information. This is distinct from a supervised artistic approach to virtual environment design where specific choices and interpretations are made to generate a single discrete scene. Whilst reference images and interpretation were used to generate the procedural vegetation/land system classes (with a rules-based approach) (see figure 6.3), the way these classes were distributed across the landscape was controlled by the land cover models already generated throughout the rock art research presented in this thesis (see chapters 2, 4, 5). This allows researchers the chance to visualise data in a new way without the need to first construct a visualisation in their own minds and then translate this to a graphical rendering. Data can be directly and discretely interpreted, in a piecewise manner before being combined to form the holistic digital landscape model.

The painted rock art sites recorded throughout this research were included in these simulations, however they were not depicted in this chapter in order to maintain cultural privacy and sensitivity of these important images. However, this simulation has proven capable of handling the photogrammetry data produced throughout the thesis (see chapter two) and representing the high quality textured meshes in their landscape context. This allows a user to view at an art site insitu, or remotely, and see the motifs on the rock surface immersed in the landscape environment surrounding this static art site. Importantly, using the paleogeographic modelling approach, rock art motifs of significant antiquity can be viewed surrounded by the environment that was contemporary to their inscription.

The Unreal Engine has made a variety of visualisation outputs and interactivity methods easy to prototype and deploy. The dynamically interactive environment produced goes beyond just a visualisation and could be best described as a simulation.

6.5 Conclusion

This chapter has explored and successfully demonstrated the use of dynamic VR where a user can be fully immersed and move around freely in the simulated landscape. As all the lighting used in the engine is dynamic, lighting conditions such as time of day can be changed on the fly, and shadows and shaders will respond in real time. This level of immersion and control allows dynamic exploration and telepresence to be achieved in otherwise completely inaccessible palaeolandscapes, that is, landscapes that are remote in time. In addition, this extends to highly inaccessible current world landscape locations as well, due to the dynamic virtual reality and static image renders, the Unreal Engine can develop. These 360° stereoscopic panorama images have the capacity to be used within phone mounted headset displays, providing a cost-effective way of allowing virtual reality experience of static locations within the simulated environment, which can then still be experienced with a real-world scale relative to the user. Using these phone displays allows the experience of the simulations to occur remotely, away from a computer. Critically, this has the potential to allow remote cultural engagement with heritage sites and access to provide archaeological data to people who may not otherwise be able to access these sites. This provides huge potential for use within remote Indigenous communities as well as for general education, research dissemination and tourism possibilities. Importantly, these immersive engagements allow an intuitive way of non-language-based communication of spatial archaeological data. This is of critical importance in an Australian Indigenous archaeology setting where researchers and Traditional Owners work together toward shared understanding of cultural heritage places and landscapes, and communication can often be across language and cultural barriers. The Unreal Engine and approach presented in this chapter provides a flexible, accessible and cost-effective means to provide immersive visualisation and simulation of archaeological landscapes and a wide variety of new platforms for the Unreal Engine

The approaches presented in this chapter provide a flexible, accessible and cost-effective means to provide immersive visualisation and simulation of archaeological landscapes and a wide variety of new platforms via the Unreal Engine. Where this paper has explored VR, computer-based interactivity and image renders as a means of interaction with the simulated cultural landscapes, the Unreal Engine platform has the capacity to be adapted for a wide variety of other emerging platforms which provide additional new means to visualise and interact with the simulated environments. Mixed reality, augmented reality and large-scale LED screens all offer new potential means to interact with the environments created in the Unreal Engine. Future developments in this space hold exciting potential to foster new means to facilitate the exchange of ethnographic accounts and Indigenous traditional knowledge in a collaborative virtual environment to benefit two-way communication of complex cultural heritage information.

CHAPTER SEVEN

Chapter 7: Thesis Conclusion

This chapter concludes the work of this thesis with a brief summary of the aims and innovative methodological approaches of the research, followed with a discussion and recap of the breakthrough results of these applications.

The major goal of this research has been achieved, that is, 'the need to develop digital approaches to aid in the field recording, stylistic analysis, landscape reconstruction, visualisation and dissemination practices applied to traditional Indigenous cultural rock markings'. This was identified as 'a necessary requirement to facilitate new understandings of past relationships with place and environment, speak to present day cultural heritage representations, and provide a technological bridge between historical cultural artefacts and future research requirements'. In addition to this fulfilment of intent, the major research question further identified the need for this outcome to address the varied requirements of several interested parties, which also has been successfully addressed by this work. The major research question asking:

> How can emerging digital technologies be utilised to provide new insights into Indigenous cultural rock markings while serving the values of Traditional Owners, meeting the needs of cultural heritage management, and promulgating effective communication of archaeological models of the past?

This research question has been answered through the practical development and application of digital approaches that have addressed the key components of each stage of rock art analysis from raw data collection to effective immersive communication across multiple platforms. The contributory developments of this research include the introduction of a geospatial photogrammetry-based recording approach, an innovative motif style analysis method using machine learning techniques, the reconstruction of past landscapes and palaeogeographic terrain models, the spatial analysis of sites within their extended landscape contexts, and the culmination of these separate data into a highly interactive simulation for the exploration and communication of archaeological data.

This chapter will now recap and synthesise these separate research components to discuss the contributions to our understanding of the rock art of Arnhem Land that have been produced by this combined holistic approach, and finally expand upon this work with suggestions for future developments with these technological applications in mind.

7.1 Synthesis of Thesis

This thesis has approached the analysis of rock art primarily through a comparison of the similarities and differences in style. Stylistic analysis is central to the discipline of rock art analysis, providing a framework for understanding, chronology, spatial groupings and cultural influences that are critical to interpreting rock art from an etic perspective (Conkey and Hastorf 1990; Jones 2017). Whilst established chronologies exist for the Arnhem Land region, these have been developed over decades through methods of subjective typological assessment and remain ongoing. The current stylistic categories and chronology are defined with wide scope within categorical definitions that are not sensitive to subtle patterns, regionalisation or transitional styles that occupy a shorter span between well described classes. Further to this, the primary recording of rock art sites is instigated to provide outcomes for a wide variety of uses and perspectives, broadly within the areas of heritage management, archaeological analysis and virtual site access, not necessarily all with the same requirements. The methods and outcomes of this thesis, discussed below, address and achieve the outputs required for all these purposes.

Beginning with the collecting of raw data, chapter two presented a rock art recording approach that was designed to produce datasets that can benefit all avenues of enquiry whilst providing the scope to catalogue motifs within the context of their placement across space and time. The photogrammetry approach deployed has demonstrated the ability to record rock art motifs through high resolution images, and mapping these images to a virtual geometric representation of the rock art site, typically rock shelter or boulder, then achieved extremely high detail and accuracy. In addition, the process of rock art recording was further expanded to capture the surrounding landscape using remote drone-based photography. The resultant photogrammetry recordings have provided richly detailed, georeferenced, digital models of rock art sites and their landscape, including accurate measures and mapping of topography. These outcomes allow motifs to be catalogued with the maximum context of their location, including their positioning on a painted panel, the placement of the panel in the site, and the placement of the site in the landscape. These critical detailed records allow effective visualisation management and analysis outcomes.

Following this, chapter three introduced a new approach to stylistic analysis using a transfer learning approach which leverages the pattern recognition strength of deep learning with convolutional neural networks, a facet of machine learning. This approach, which makes use of unbiased transfer learning as a one shot activation task and has never been applied in an archaeological context before which was able to independently order a given set of motifs into a sequence of similarity that agreed with established chronology without any reference to these pre-existing categories in the approach. This presents the opportunity for questions of style to be asked at any scale and applied to any data set in order to explore the relationships that are present within that given set. Proving this concept, when provided with a dataset that included comparable human depictions from a range of styles and geographic provenances, a stylistic gradient was produced that separated styles into the same order as existing chronologies. Each pre-established style group clustered together without direct training with these known labels, demonstrating a purely stylistic patterning which matched existing chronological interpretation. This result also accurately clustered motifs based on their geographic provenance. Motifs from the same stylistic phase, yet different regions of Arnhem Land, were grouped nearest their geographic contemporaries, but still in the correct region of the overall stylistic gradient to match the chronological phase. This approach reinforces the validity of the many years previous research and debate around rock art styles in Arnhem Land and offers a new quantitative method to assess style to help to increase the efficiency and clarity of debate in this context.

This result demonstrates the approach's ability to recognise and quantify subtle regional differences within broader style trends. The stylistic gradient shows that the styles analysed were linearly related to one another over time, suggesting a gradual stylistic progression with local regional uniqueness, occurring within the pan-Arnhem stylistic progression. One style that did not plot neatly into this linear gradient however, was the Northern Running Figures (NRF). These Figures have a very focused geographic distribution and have been identified within the literature as having a number of possibly different cultural functions to their contemporary or temporally adjacent styles (Jones 2017; Jones et al. 2017b; Jones and May 2017). Here the placement of the NRFs within the stylistic gradient agrees with the literature on this style’s distinction from the other classes and demonstrates that this distinction extends into its actual stylistic design.

To provide context to each part of the stylistic chronology, an understanding of the nature of environmental changes is required. Here, chapter four determined a geophysical and geomatic based approach to the modelling of palaeogeography in the area. This chapter used the regional models of environmental and palaeogeographic change to inform the interpretation of geophysical and geomorphological data. The results showed that an extensive buried Pleistocene land surface lies 10-15 meters below the contemporary floodplain. This land surface includes a large, buried sandstone shelf which extends under the contemporary floodplain and has an extensive escarpment which likely offered a wide variety of rock shelters and other suitable habitation and rock art inscription sites. This Pleistocene land surface is overlain by thick mangrove mud which records a dramatic sea level transgression which was able to reach this local area 50km away from the contemporary coast. In this way the palaeogeographic models produced demonstrated the dramatic effects of the post glacial marine transgression reaching the sandstone escarpments of the study area. Whilst the effects of the marine transgression were known on a regional scale, it is critical to provide direct local relevance to these broad models in order to make appropriate interpretations of rock art in their true landscape context. The impacts of the transgression on the palaeogeography of the study area had previously been unknown and underestimated in the existing broad regional models.

The combination of the site recordings, stylistic analysis and palaeogeographic modelling allowed the spatial modelling of rock art sites to be conducted to understand patterns of site placement. Chapter five presented an approach which took geographic models and archaeological site records and analysed the use of space through the key periods of past environment and palaeogeographic configurations. This approach was developed to be sensitive to more than just the placement in the environment but also to the detection of some elements of the human sense of presence discernible through the use of visibility analysis. The results proved significant differences in the placement of rock art throughout the landscape over the key four past environmental phases, supporting previous studies that suggested higher elevation sites were preferentially selected during earlier phases in the later Pleistocene and early Holocene. This approach was also able to demonstrate the differences in the landscape areas that were visible during these earlier phases compared to the mid and late Holocene. A significantly different distribution in the elevation of Northern Running Figures was found which further supports the findings from the machine learning analysis of style (chapter three) and the previous literatures' suggestion of a distinct cultural function associated with this art style. Chapter five demonstrates that combining the palaeogeographic modelling and site recording methods used in this overarching approach allows the detection of major changes in the ways people used space and the perception of landscape at rock art sites, adjusting to the landscape environment changes over time.

To synthesise the multitude of data collected throughout this thesis, including the complex archaeological models of the past landscape and the past environmental changes and palaeogeography, chapter six presented a novel workflow using the Unreal Engine to visualise archaeological data. In this application the various types of data produced throughout the site recording and landscape modelling were imported and then the landscape components each of these data sources were simulated to be represented in a visually realistic way. Ultimately this approach allowed not only visualisation of the combined datasets as a near to photorealistic rendering of the combined landscape, but also allowed a full simulation of this environment to be explored in virtual reality. This approach opens the way to anew means of understanding archaeological landscapes and communicating them between researchers and a variety of audiences in a way that takes advantage of telepresence and the innate human intuition of space, though visual and accurate scale and viewing angel (relative to a human observer), to communicate data that is usually communicated in an abstracted, at times confusing way.

Each section of this thesis contributed to both a novel methodological approach to the various components of rock art research as well as an archaeological understanding of the study area. The approaches presented throughout support each avenue of rock art research while demonstrating a way to construct these separate elements to work together to support a larger holistic landscape analysis. The final simulations in Unreal Engine represent a completely different way to combine these datasets to support the models produced and communicate the full complexity of the past realities they model. This achieves a major goal of landscape approaches, in this case applied to rock art research, to continue to reduce the abstraction of spatial data and open it to the experiential human perspectives of landscape impact.

7.2 Future Directions

This thesis has developed and successfully applied a number of new approaches which have expansive potential for future developments, both in their application within archaeological research in the Greater Red Lily Lagoon region as well within their expansion to the larger archaeological discipline, particularly in the area of rock art research more broadly. Following is a brief discussion and concluding remarks regarding these new technologies including possible future directions for their use as archaeological research applications.

7.2.1 Machine Learning for Archaeology

Machine learning, as introduced in chapter three, has provided an opportunity for a new way to quantify stylistic elements and material characteristics that have previously been limited to the domain of subjective approaches. Machine learning has proven capable of finding mathematical structure for human cultural and artistic expression (Karayev et al. 2013; Shamir et al. 2010). This approach has utilised the transfer learning and one-shot classification to overcome the need for large archaeologically specific training datasets, which has previously hampered the application of machine learning in this field. This thesis has presented an approach which leveraged the internal mathematical structure of these learned features in order to provide a means to organise an assemblage of motifs by their innate artistic visual elements. This organisation has proven the ability to provide a continuous and seamless gradient to the degree in which an assemblage can be organised, rather than relying on widely defined criteria for each typological class. This demonstrates the ability to distinguish chronological and geographic elements and group motifs accordingly, which provides a means to increase sensitivity to regional, temporal, and individual influence on style. This increased sensitivity has the potential to operate similarly within the same theoretical perspectives in a landscape, cultural boundary, or social identity application, recognising established criteria while providing new insights into previously unexplored nuanced regional specificities within style.

This has an incredibly wide range of uses within archaeology globally, particularly in Australia where a huge diversity of distinct Indigenous cultures exists, each with unique artistic customs and expressions. This allows the approach developed to expand to ask larger regional questions about cultural influence to understand the past cultural interconnections during distinct periods of rock art production across a much wider region of the continent. Additionally, approaching the stylistic gradient in a much more sensitive way may also expand the possibility to allow the identification of specific artists, or clan groups, who share a distinct artistic repertoire that fits within a larger regional or temporal artistic style. Both the questions of larger patterns of artist influence, as well as the challenge of identifying smaller subgroups within known regions and categories, are limited only to the application of this approach to an appropriately sampled dataset.

As a first of its kind this approach was developed using only monochromatic line tracings of motifs in order to ensure that there was not stylistic influence from the rock background, faded colours or superimposed motifs. One immediate avenue of advancement to this approach would be inclusion of coloured lines in the traced dataset, representing the ochre colours of the motif. This will allow patterns in the changing use of colour to be encoded into the overall stylistic scheme produced. A second advancement would be the further investigation of direct photography classification or semantic image segmentation in order to speed up the workflow and avoid the need to trace images.

Whilst the approach presented has focused on two-dimensional artwork, it has the theoretical potential to be expanded to three-dimensional structure. The similar development of a transfer learning approach to produce a stylistic gradient of three-dimensional data requires only minor modification opening the possibility to a new way of detecting patterns within stone tools, pottery and ceramics, nautical technology as well as any number of archaeological assemblages where multiple styles exist.

The achievements of the transfer learning approach have made use of stylistic learning performed on an unrelated dataset that does not contain cultural artistic depictions yet has still allowed the encoding of the concepts of stylistic similarity in a neural network. This demonstrates the incredible potential of machine learning for the understanding of style. Other unrelated advances in machine learning have leveraged this same learning in stylistic domains to produce style transfer, where an art style can be learned and then applied to an unrelated image to produce a representation of this image in the learned style (Jing et al. 2019; Sheng et al. 2019). This presents major new ethical considerations for the use and impacts of machine learning approaches as applied to artistic styles which represent Indigenous cultural and intellectual property (Janke and Quiggin 2006). This is only one example of the potential ethical issues that may arise from the emergence of new technology in this space, indicating the need for future research to address such ethical challenges.

7.2.2 Geophysics for Palaeogeographical Modelling

This thesis demonstrated the use of the Electrical Resistivity Tomography (ERT) geophysical technique to resolve distinct subsurface resistivity boundaries which represent buried sediments and geology. This method allow rapid cost-effective geomorphological modelling, in this case, of the Alligator rivers, which will provide significant insights into the palaeoenvironments and associated past human activity in this region. Presently these palaeogeographic models have been constructed through geomorphological interpretation of resistivity results informed by local regional models. This interpretation can be validated and improved through direct subsurface sampling through coring, in the regions where ERT data has been collected.

Previous regional models of this area have been constructed through extensive coring and excavation, which provides reliable results, but is a time consuming, invasive and very expensive approach (Wasson 1992; Woodroffe 1988; Woodroffe 1993; Woodroffe et al. 1989; Woodroffe et al. 1986; Woodroffe et al. 1985). The rapid sampling that is achieved through ERT has been demonstrated to be capable of subsurface modelling in this region and can leverage these results to expand and refine regional models to more isolated and unsampled regions of the Alligator river floodplains, as demonstrated in the study area of this thesis.

This work used ERT to detect a buried sandstone escarpment which was interpreted to be buried during the middle Holocene and represents a feature likely to have habitable shelters during the Pleistocene and much of the Holocene. This is a significant clue towards understanding the sparsity of Pleistocene aged occupation sites in the region despite the proven presence of people during this time. The ERT approach offers a cost effective and rapid means of expansive sampling of the floodplains and sandstone boundaries which are likely to hold more occupation sites from this period.

The results of the ERT survey in the study area also revealed a Pleistocene aged land surface with clearly visible incised palaeochannels. The ability to model and map the hydrological landscape during the Pleistocene is another area of major potential for future application. Expanding these models of the Pleistocene landscape and environments, has the significant potential for future prospection of Pleistocene occupation sites which may hold significant narratives for the early occupation of the continent.

ERT has been demonstrated to be capable of the detection of subsurface shell middens (Kenady 2016). This expands the future application potentials of this technology for the Alligator rivers region to allow more specific sampling of palaeochannel banks for the explicit detection of subsurface sites.

7.2.3 Immersive Experience of Virtual Cultural Landscapes and Conclusion

This thesis introduced a new approach to simulating archaeological models of the past, based on actual archaeological data, processed using the Unreal Engine development platform. This allowed the representation of archaeological models of palaeolandscapes with highly realistic graphics. The platform was developed to allow fully immersive virtual reality interactions as well as the virtual reality experience of static positions within the landscape through mobile headsets. These systems were deployed to allow the experience of archaeological landscape models to be as intuitive and familiar to a natural experience of place and possible. These platforms have achieved this goal and open up a wide array of possible new platforms of immersive experience of archaeological landscapes including Mixed Reality, Augmented Reality and the use of immersive spaces, outlined below.

Mixed reality allows the inclusion of real-world objects or tactile representative props to be included in simulated environments being engaged with through virtual reality headset (Benford and Giannachi 2011; Rokhsaritalemi et al. 2020; Speicher et al. 2019). This offers the opportunity to include new mechanisms for interaction with material cultural or representative props within these simulated virtual cultural landscapes. Augmented reality allows the real world and simulated world to be blended often by using a camera attached to a headset and allowing the simulation to augment the sensory experience of the real world (Benford and Giannachi 2011; Rokhsaritalemi et al. 2020; Speicher et al. 2019). This has some challenges for adaptation, but the Unreal Engine approach is adaptable to include the actual exploration of contemporary environments in their true location to be augmented with elements of the created past simulations on a full landscape scale. Immersive spaces are spaces which have deployed many large screens for projectors in order to surround and immerse occupants in the virtual world without the use of a headset. This offers a collaborative experience of virtual places. All of these immersion technologies have great potential to further extend the benefits of archaeological landscape simulations. This is especially promising for use in an ethnographic research context, where collaborative virtual immersion or the practical exploration of contemporary landscapes while using AR platforms, may offer many cognitive and communicative benefits to an archaeologist's interaction with Indigenous knowledge holders. Importantly, all of these platforms also have the potential to facilitate new ways for Indigenous cultural custodians and members of descendant communities to experience their cultural heritage from a remote place or in regard to a remote time, using virtual simulations. Australian rock art research has a foremost responsibility to facilitate the effective communication and exploration of archaeological data and models of the past to Indigenous Traditional Owners. The many new future developments that can emerge from the Unreal Engine workflow offer the exciting and timely possibility to strengthen Indigenous knowledge holders' contribution, comprehension and engagement with archaeological research outcomes.

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