



A changing perspective: the impact of landscape evolution on rock art viewsheds

Jarrad Kowlessar¹ · Daryl Wesley¹ · Mark Willis^{1,2} · Ian Moffat¹ · Tristen Jones³ · Shay Wrigglesworth^{4,5} · Alfred Nayinggul⁴ · the Njanjma Rangers

Received: 23 January 2023 / Accepted: 30 November 2023 / Published online: 28 December 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Arnhem Land, which has one of the longest records of human activity on the Australian continent, also holds one of the most important 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 at least 28 thousand years, during which time the region has undergone significant environmental and palaeogeographical changes. Rock art research in the area, however, has not considered high resolution palaeolandscape data, but rather has used coarser scale regional environmental models. This paper addresses this issue, applying detailed palaeogeographic modelling of current and former landscapes 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 site placement strategies for rock art in the region, which appear to relate to four key phases of the landscape change that have occurred from the late Pleistocene to the late Holocene.

Keywords GIS · Visibility · Rock art · Landscape · Palaeolandscapes · Sensory archaeology

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. 1994a, b; 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 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 1989a, b, 1993; Taçon et al. 2020), and linked rock art to changing environmental conditions to establish regional chronologies (see Chaloupka 1993). Recent geomorphological characterisation of the Greater Red Lily Lagoon Area (GRLLA), a province of exceptional archaeological significance in Arnhem Land, Australia (see Fig. 1), has made an environmental interpretation of the rock art sites in this landscape possible with an unprecedented level of detail (Kowlessar et al. 2023). In this work, Kowlessar et al. (2023) connected four distinct past environmental phases with distinct palaeogeographical configurations, that is palaeolandscapes, of the East Alligator River region. Figure 1 shows the East Alligator River region along with the GRLLA study area.

An innovation proposed in this paper is the linking of rock art distribution to digital modelling of these palaeolandscapes in the East Alligator River region, utilising high resolution elevation data. This is achieved through detailed topographic elevation modelling, paleogeographical reconstructions and viewshed analysis which provides information about what can be seen from each rock art site at the appropriate environmental period.

✉ Jarrad Kowlessar
jarrad.kowlessar@flinders.edu.au

¹ Archaeology, College of Humanities, Arts and Social Sciences, Flinders University, Bedford Park, Australia

² Sacred Sites Research, Albuquerque, NM, USA

³ Archaeology, School of Humanities, Faculty of Arts and Social Sciences, The University of Sydney, Camperdown, Australia

⁴ Njanjma Rangers, Kakadu, Australia

⁵ Kakadu National Park, Kakadu, Australia

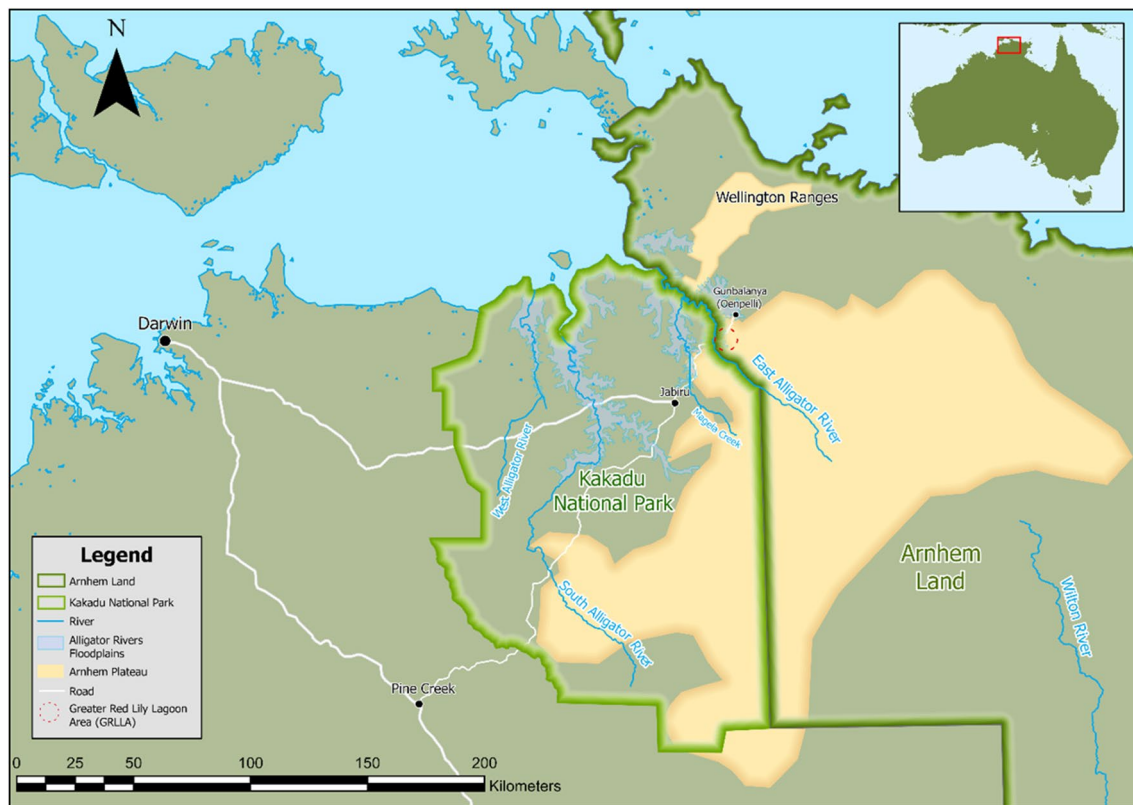


Fig. 1 Map of the study area within the larger region, showing the Alligator rivers, floodplains, Kakadu National Park and Arnhem Land along with the Arnhem Plateau (for detail of the study area, see Fig. 2)

The rock art, archaeological sites and other Indigenous cultural places of the GRLLA have national heritage significance. The rock art in the GRLLA has been directly dated to the Pleistocene–Holocene transition with production continuing 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 its contemporary and past environments, this paper provides unique insights into settlement strategies and human adaptations throughout these periods, adding to the current understanding of this significant area.

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/or social complexities, as well as to understand broad relationships to the environment (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 and/or the spatial distribution of sites. In this

way, artistic style is viewed as arising as a cultural function and is tied closely with social identity (Conkey 1980: 609; McDonald 2017; 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, 1989, 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, 1989, 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, such as style, subject matter and site type, can be associated with increased population size, information exchange, 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 homogeneous 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, 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 place 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 extend 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 from 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; David et al. 2014; David and Thomas 2016).

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; Tilley 1994; Wheatley and Gillings 2000). 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) or within caves (Intxaurbe et al. 2021, 2022). The analysis of rock art through visibility has been based around two major perspectives: 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 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 clearly correlate to areas of human mobility and transit. Negative correlations may indicate deliberate hiddenness. The difficulty of assessing the hiddenness of rock art 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. An assessment

of the visibility of the rock art from the landscape of the GRLLA region is outside the scope of this research, which instead focuses on the visibility of the landscape from the rock art site from the perspective of the inscriber.

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 been 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.

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 Figures, 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 1 describes each of these distinct styles, limited to those which have been found to appear in the GRLLA study area.

Environment and rock art chronology

The GRLLA is situated on an important boundary between the ‘stone country’ of the Arnhem Plateau Kombolgie Subgroup sandstone, and the vast floodplains of the Alligator rivers (see Figs. 1 and 2). Human occupation for over 60,000 years of the region where the sandstone escarpment and floodplains interface has been demonstrated, 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 for at least 28,000 years in Arnhem Land has been demonstrated, but likely has occurred for much longer (David et al. 2013). 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, b, 2020; Taçon et al. 2020). The palaeogeography of the area has substantially changed over this period of rock art inscription, with major landscape changes associated with post glacial sea-level rise and increased precipitation (Kowlessar et al. 2023; Wasson 1992; Woodroffe 1988, 1993; Woodroffe et al. 1985, 1986, 1989).

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 Transgressive) phase, Big Swamp phase, and Freshwater Floodplain (hereby referred to as the Freshwater) phase. These phases were used 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

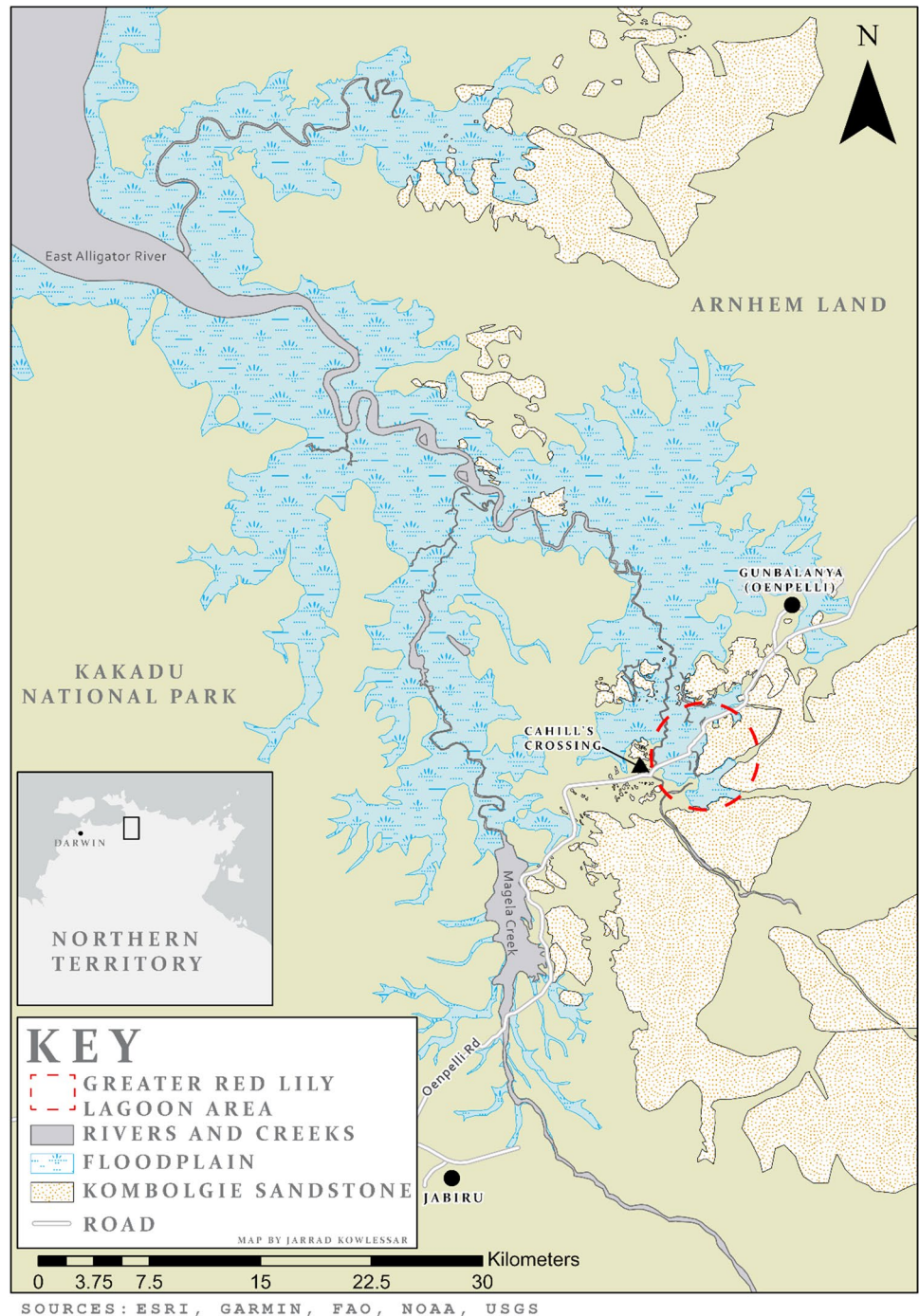
Table 1 Rock art styles of Arnhem Land found within the Greater Red Lily Lagoon region

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; Johnston et al. 2017)
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 such as optic nerves, internal organs and spine. These are more limited in internal detail than the more recent X-Ray style (Jones et al. 2017)
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)

the Arnhem Plateau highlands down through the low-lying valleys to the north (Wasson 1992; Woodroffe 1988, 1993; Woodroffe et al. 1985, 1986, 1989). 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 levels, which would have impacted these fluvial systems in ways that 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 elucidated the pre-transgressive fluvial landscape (Kowlessar et al. 2023). This fluvial landscape would likely have been active in the area since the previous interglacial cycle and is characterised by smaller creeks and streams running through open woodland (Kowlessar et al. 2023).

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 characterised 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. 2015, 2017; 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 from when it occurred distantly from the study area through till 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 to 50 km inland from the coast (Taçon and Brockwell 1995; Williams et al. 2018).

Fig. 2 Map of the East Alligator Region showing the Greater Red Lily Lagoon Area, East Alligator River floodplains and sandstone outcrops of the Kombolgie Subgroup



It is clear from the amount of land submerged that a great number of people must have been displaced, which is reflected by an interpreted 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 would have caused alterations to social boundaries, trade networks, and resource availability and may have resulted in a restructuring of boundaries and clan relationships (Blainey 1975: 90–91; Veth et al. 2021; Williams et al. 2018). The large 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 response to the dramatic climate change events that began around this time and continued

into the mid Holocene (Blainey 1975; Jones 2017; Norman et al. 2024; 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 produced further seaward in areas that are now inundated (Chaloupka 1993; Chippindale and Taçon 1998; Reeves et al. 2013a, b; 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 (Johnston et al. 2017: 113). This extensive distribution has been interpreted as an indicator of past social–cultural boundaries and inferred lifeways and as 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 possibly associated with 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 (Lewis 1997; Veth et al. 2021; Yokoyama et al. 2001).

The first appearances of large battle scenes within the rock art of the region seem to be associated with post-glacial sea level rise (Taçon and Chippindale 1994). Whilst 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 (Blainey 1975: 90–91; Lewis 1988: 90; Taçon and Brockwell 1995: 121). These battle scenes have been more recently interpreted as depictions of ritual rather than actual combat (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 suggests that

the Alligator River region may have been a point of contact between locally established groups and displaced people, especially towards the end of the sea level rise. The GRLLA is located at the boundary between the lowlands of the river valley and the stone plateau, leading to 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) as well as an abundance of biodiversity, an important factor in Indigenous subsistence practices (Wesley et al. 2017: 25). Furthermore, riverine corridors are particularly important in sandstone environments where they act as a highly traversable vector.

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 is differences between individual artists rather than a cultural regional separation (Johnston et al. 2017: 122). This model implies that during this time only a small number of individual artists may have been active and that they may have made 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 using 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. 2017a, b). The NRF style has a very limited distribution across Arnhem Land which is centred 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; Chippindale and Taçon 1998). These three styles are therefore included with our Sea Level Rise phase.

Large Naturalistic Styles can appear throughout the chronology and are difficult to associate with a particular phase; however, they are sometimes associated with the

pre-estuarine environmental phase, based on superimposition chronology (Jones et al. 2020).

Transgressive 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 stabilised. This phase differs from the Sea Level Rise phase because it represents the time when the marine transgression had reached far enough inland to influence the waterways valleys of the GRLLA study area which had previously remained freshwater fluvial system. The transgression rapidly and extensively flooded the low-lying valleys of the Alligator rivers (Wasson 1992: 55–56, 141; Woodroffe 1993). This flooding has been modelled as a total filling with ocean that effectively created at least a temporary coastline along the edges of the modern floodplain valley (Wasson 1992: 55–56, 141; Woodroffe 1993). This transgression extended into the GRLLA, directly up to the sandstone escarpment (Kowlessar et al. 2023) significantly reducing the area of available land.

The NRF style is likely to have occurred well into this phase, 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 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 been dated to 9,260–9,540 cal. BP based on an indirect association with an ochre crayon (David et al. 2017). Owing to the ambiguity of this date, the Simple Figures with Boomerangs style is still dominantly associated with this Transgressive 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 (Lewis 1988; Taçon and Brockwell 1995: 121). 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 and Brockwell 1995: 121). The Rainbow Serpent has also been argued to be an important force of cultural unification, and its ceremonial use can represent unity amongst groups and highlight aspects of shared heritage and origins (Lewis 1988; Taçon and Brockwell 1995; Taylor 1996). 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, 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 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. 2023; Woodroffe 1993). The timing of the mangal forest development varies amongst 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, where the distribution began to reduce 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. 2023). The sedimentation caused by these mangroves infilled and overlay sections of sandstone escarpment along the floodplain edges within the GRLLA (Kowlessar et al. 2023). This indicates that many of the possible occupation locations of the early part of the Big Swamp phase in the region are now covered by floodplain sediments (Kowlessar et al. 2023).

A clear shift in archaeological site usage during the Big Swamp phase has been observed within the excavated assemblages from the area (Allen 1989; Allen and Barton 1989; Clarkson et al. 2017, 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 (Allen and Barton 1989; Clarkson et al. 2017; Hiscock 1999: 94). 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; Chaloupka 1993; Lewis 1988).

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 and Barton 1989: 104). This restriction may have made crossing the lowlands difficult and limited movement and settlement location to the plateau's margins and valleys, along with limited lowland corridors amongst tidal floodplains (Allen & Barton 1989: 104).

The changes in lithic technology through this period coincide with the appearance of new technologies depicted in the rock art, including a high diversity of spear types and spear throwers (Chaloupka 1993; Chippindale and Taçon 1998; Lewis 1988). 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 amongst scenes with boomerang depictions. Otherwise, simple figures are typically assigned to the more recent 'Simple Figures' class (Chaloupka 1993; Chippindale and Taçon 1998; Lewis 1988). 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 substyles of simple figures have been constructed from regional typologies (Lewis 1988: 34–38) as well as more recently being characterised using machine learning (Kowlessar et al. 2021). Both approaches have characterised the Simple Figures regional substyles as being collectively part of a larger Simple Figures class which occurs over the entire Arnhem Plateau, yet still 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 based on social reorganisation associated 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 that usually depicts yams or 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 on overlying mud wasp nests and calcium oxalate mineral crusts. This date provides a minimum age of 5,068–6,666 cal. BP for this style (Jones et al. 2017a: 87). This age confirms this style's placement within the Big Swamp phase.

Large Human and Large Fauna figures are also associated with the Big Swamp (Chaloupka 1993; Chippindale 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 within the same region, and sometimes on the same 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 4400 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 led to significant sediment accretion at the same time 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 large 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. 2023; Wasson 1992; Woodroffe 1988, 1993; Woodroffe et al. 1985, 1986, 1989).

Peak lithic production occurred during this time, related to major changes of resource availability (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.

As progradation progressed, new regions of sinuosity developed further seaward in the Alligator Rivers, and

the flow rate through old river meanders increased as fluvial dominance overtook marine forces in these upstream extents. The increased flow rate through former river meanders erodes riverbanks leading to sharp cusps in the channel morphology. This period, referred to as the Cuspate phase, followed the Sinuous phase of river morphology and is associated with 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 to 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 2,000–1,000 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, 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, Complete Figure Complex, Beeswax Figures and X-Ray rock art emerged (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 (Taçon 1989a; Taylor 2008a, b). This period of art displays a vivid use of colour and decorative patterns 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 connection with clan country (Taçon 1989a; Taylor 2008a, b). 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.

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 actively occupied 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 to be produced 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 other locations. 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. For this reason, there is merit to investigating elevation of sites directly.

Geomorphology and land cover classes

Kowlessar et al. (2023) 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 Subgroup 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 Subgroup 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 2 shows the land cover classes as defined in this study and their connection to the landforms within the study area.

Methods

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. 2022; 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. Distinct sites were determined where a physical break between archaeological features of at least 10 m occurs. 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. (2022). 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 to group the rock art data by environmental phase. Large Fauna was not included in these chronological subsets due to the ambiguity in correct chronological identification (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 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 3 shows the styles recorded and their grouping based on their environmental phase.

Land cover analysis

A supervised land cover classification was performed for the entire study area. The study area was categorized into one of the following labels: River, Floodplain, Backswamp, Colluvium, Sandstone, Monsoon Vine Thicket, Open Eucalypt Woodland and Paperbark Woodland. Figure 3 demonstrates these land cover classes and their landscape and geomorphological context along with subsurface features (Kowlessar et al. 2023).

This classification was performed using manual tracing of satellite images, and aerial photography along with ground visits and photographic records for validation. These 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.

Visibility analysis

A digital elevation model (DEM) was created 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. 2022). 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 generate a complete coverage of the study area which was 175.93 km².

A second DEM recreating pre-transgression elevations was derived from this contemporary elevation model by adjusting the major geomorphological component elevations based on the results presented in Kowlessar et al. (2023). Areas of contemporary floodplain were lowered by 7 m from their present day, 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 current elevations. These changes follow the regional paleo environmental model presented in Kowlessar et al. (2023). This model is based on sparsely sampled coring, geophysical data and larger scale geomorphic models and represents the most detailed model of landscape change produced for the region to date. It should be noted, however, that this model has not been validated for all areas within the study area and future interpretation of these results may be subject to changes or refinement.

Table 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, b)

Landscape classes	Vegetation	Geology	Landforms
Sandstone	Complex mosaic of woodlands mixed with shrublands with <i>E. miniata</i> (Darwin Woolly Butt), <i>E. tetradonta</i> (Stringybark) <i>Corymbia</i> sp. (variable-barked Bloodwood), low open woodland with <i>Plectrachine pungens</i> (Curly Spinitex) 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 m high. Surface is mostly bare rock or shallow sandy soil. Forms sandstone tors, plateforms, major escarpment features, and large rounded highly weathered hills
Colluvium	<i>E. miniata</i> (Darwin Woolly Butt), <i>E. tetradonta</i> (Stringybark), <i>E. bleeseri</i> (smooth stemmed bloodwood), <i>E. tectifera</i> , <i>E. tintinnans</i> (Salmon Gum) open woodland with <i>Sorghum</i> sp. grassland understory	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. Supporting woodland to tall forest with tall grasses
Floodplain	Mixed closed-grassland and sedgeland consisting of <i>Eleocharis</i> swamp, <i>Oryza</i> swamp, <i>Hymenachne</i> sp. and <i>Pseudoraphis</i> sp. grassland and <i>Fimbristylis</i> sedgeland	Alluvial and estuarine sediments	Sediment actively prograding over the finer grained deposits of the estuarine plains. Seasonally inundated during the annual wet season. Extensive freshwater swamps and paperbark forests
River/creeks/lagoons	<i>E. papuana</i> (Ghost Gum), <i>E. polycarpa</i> (Swamp Bloodwood) woodland with grassland understory. Wild rice (<i>Oryza rufipogon</i>) and the spike rush (<i>Eleocharis dulcis</i>) found in lagoons	Fluvial, alluvial, and estuarine sediments	Inland sections of the major river courses. Commonly forms levees and inter-channel bank deposits
Backswamp	<i>Melaleuca</i> forest, <i>Oryza</i> swamp, <i>Hymenachne</i> sp. and <i>Pseudoraphis</i> sp. grassland and <i>Fimbristylis</i> sedgeland	Alluvial and estuarine sediments overlying sandstone	Permanent wetlands forming over outer edges of the floodplain with sediments overlying shallow sandstone
Paperbark swamp/woodland	<i>Melaleuca</i> forest with <i>Melaleuca leucadendra</i> , <i>Melaleuca cajuputi</i> and <i>Melaleuca quinquenervia</i> 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	<i>E. miniata</i> (Darwin Woolly Butt), <i>E. tetradonta</i> (Stringybark), <i>E. bleeseri</i> (smooth stemmed bloodwood), <i>E. tectifera</i> open forest with <i>Sorghum</i> sp. grassland understory	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	Vine forests grow in some gorges and on plains where there are permanent springs

Table 3 Styles and environmental phase grouping

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

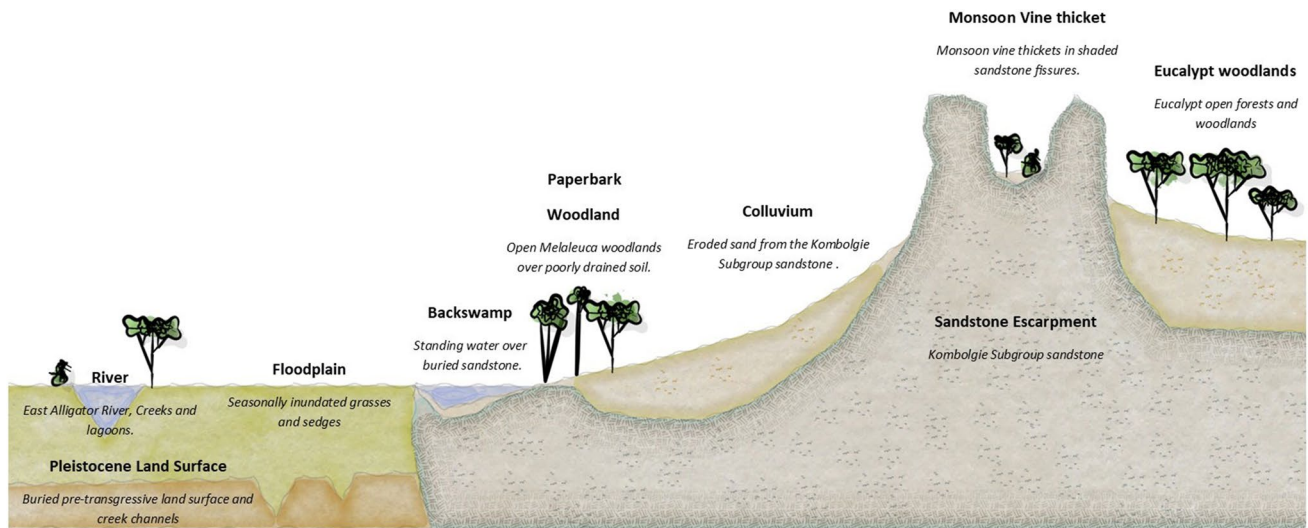


Fig. 3 Conceptual diagram of land cover classes and geomorphology of the GRLLA

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 adjusted DEM surface which

represents an interpreted pre-transgression elevation model for the area.

The total area (km²) 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 m²) and finally divided by 10⁶ to give area in square kilometre units (km²).

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 Transgressive phases, which measured visibility based on both 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 between 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 amongst 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 an arbitrary 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. This between phase comparison as a percentage of the total for each phase mitigates some effects of possible taphonomic and conservation issues that may influence the frequency of sites from older phases.

Statistical analysis

A statistical analysis was conducted to compare the distributions of the Elevation and Total Area of Visibility amongst each artistic style (see styles in Table 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 amongst groups, for example, NRF 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.

Results

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 Transgressive phase, 72 with the Big Swamp phase, and 47 with the Freshwater phase. Whilst 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 $n = 174$). Table 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.

Figure 4 displays the distribution of rock art sites throughout the landscape for each phase.

Visibility analysis

Figure 5 shows the viewshed analyses 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, 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 is given as a percentage per phase to allow comparison amongst the phases. The percentages are calculated per phase, so a pixel with a percentage of 60 (represented in red colour in Fig. 5) 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

Table 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
Transgressive	1500	30	20
Big Swamp	2400	72	30
Fresh Water	4400	47	11

during the Sea Level Rise and Transgressive 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 (see areas in red).

Fig. 4 Site placement density by environmental phase: **a** Sea Level Rise phase, **b** Transgressive phase, **c** Big Swamp phase, and **d** Freshwater phase



Fig. 5 Areas visible from sites and frequency of site visibility (%) by environmental phase: **a** Sea Level Rise phase, **b** Transgressive phase, **c** Big Swamp phase, and **d** Freshwater phase

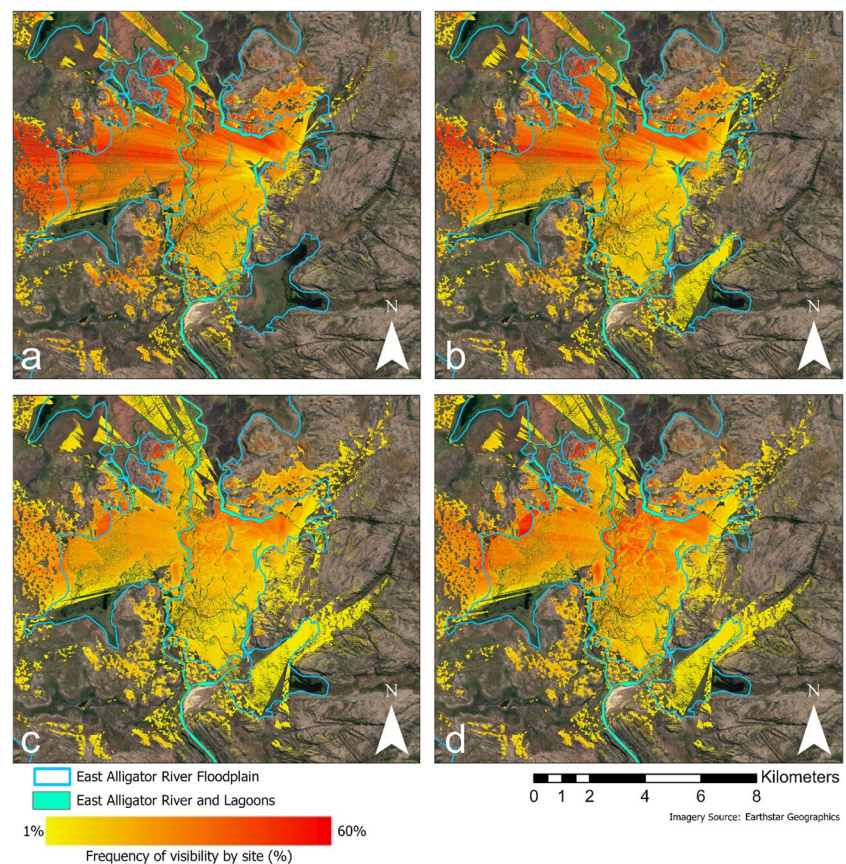


Table 5 Mean site visibility and elevation by environmental phase

Phase	Visibility (SD) km ²	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)

SD standard deviation, *AHD* Australian Height Datum

Statistical analysis

Table 5 shows the mean and standard deviation (SD) for the elevation (m Australian Height Datum [AHD]) and area of land surface visibility (km²) for each group. Figures 6 and 7 show the elevation and visibility by phase respectively.

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. Figures 8 and 9 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 amongst 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 amongst the NRF style and all other styles except for Yam figures and Simple Figures with boomerangs. No significant differences were shown between any other style pairs indicating only the NRF has a significant difference in elevation distribution amongst the styles.

The Kruskal–Wallis test found that the distributions of site total visibility areas were not significantly different amongst the artistic styles.

Greater Red Lily Lagoon area land cover mapping and analysis

Figure 10 shows the map of the land cover classes produced for the full study area, which is the extent of the visibility analyses.

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. Figure 11

Fig. 6 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)

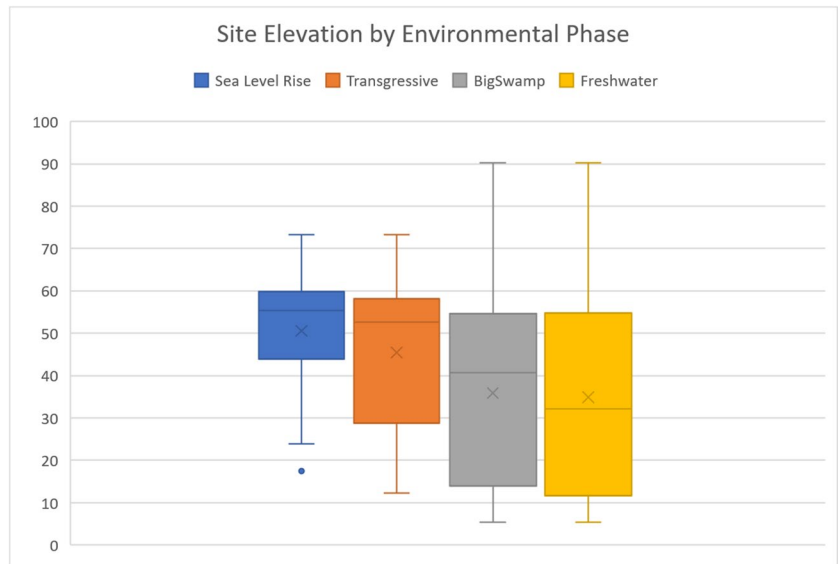


Fig. 7 Box plot of site land surface visibility (km²) by environmental phase. *x* represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range). Sea Level Rise Pleistocene LS and Transgressive Pleistocene LS show the 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

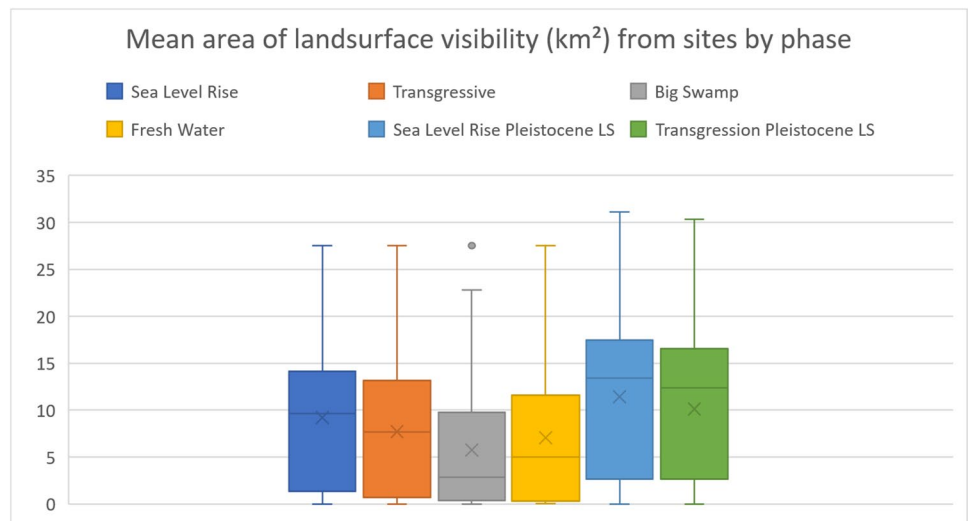


Fig. 8 Box plot of artistic style by site elevation (m Australian Height Datum [AHD]). *x* represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range)

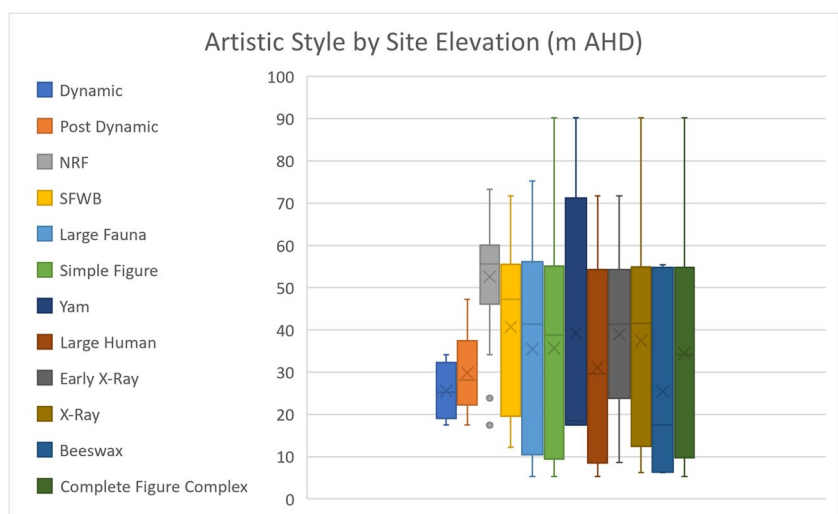
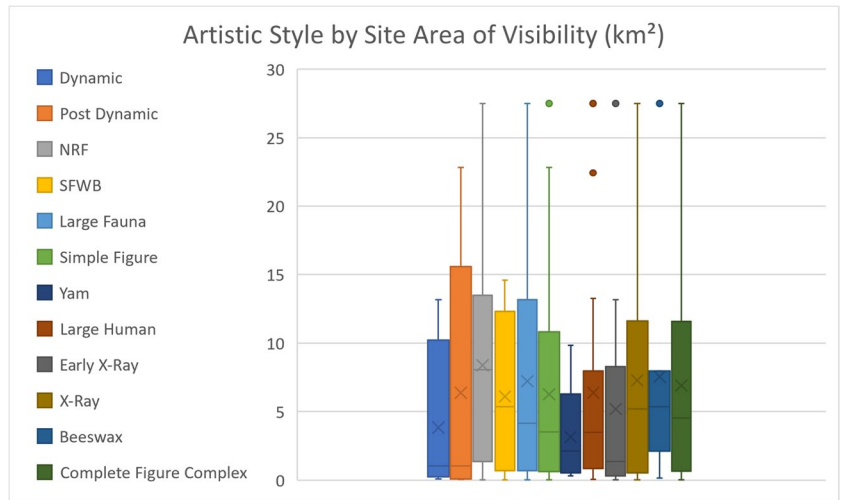


Fig. 9 Artistic style by site area of visibility (km²). *x* represents the mean value for each phase and dots represent outliers (values which fall outside of the inter quartile range by 1.5 times this range)



shows these values as a percentage of the total visible land surface for each environmental period allowing comparison to each other.

Figure 12 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 13 shows the area of each land cover class that occurred within 100 m of a site as a percentage of the total area 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

Fig. 10 Land cover map of the study area today. The boundaries of this map represent the extent of the visibility analysis

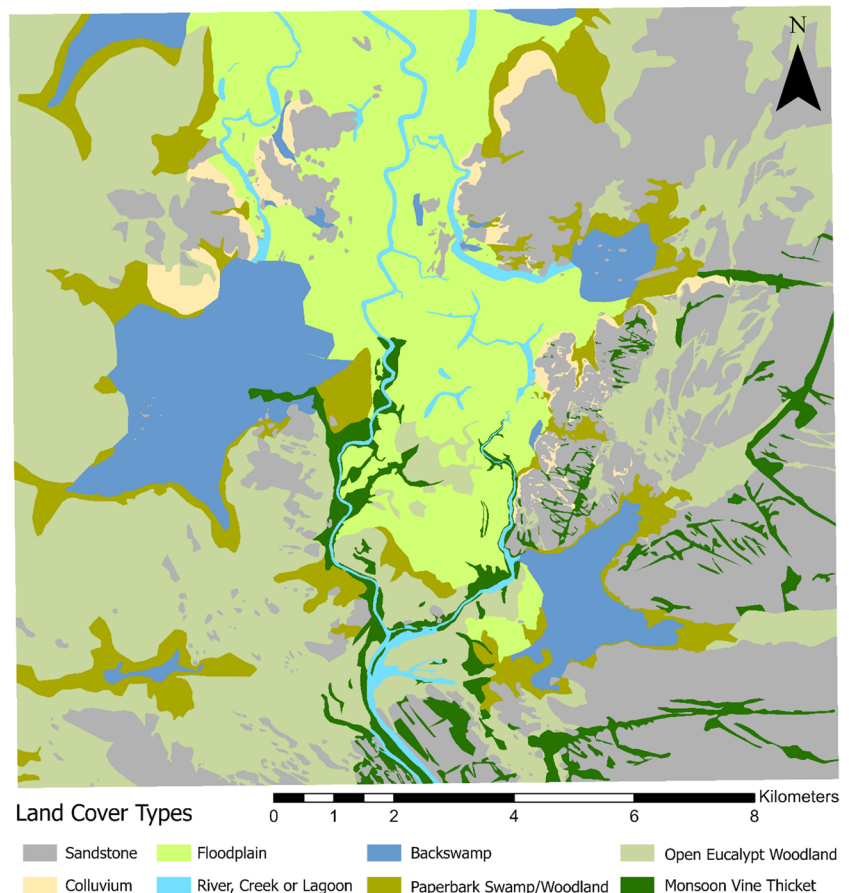
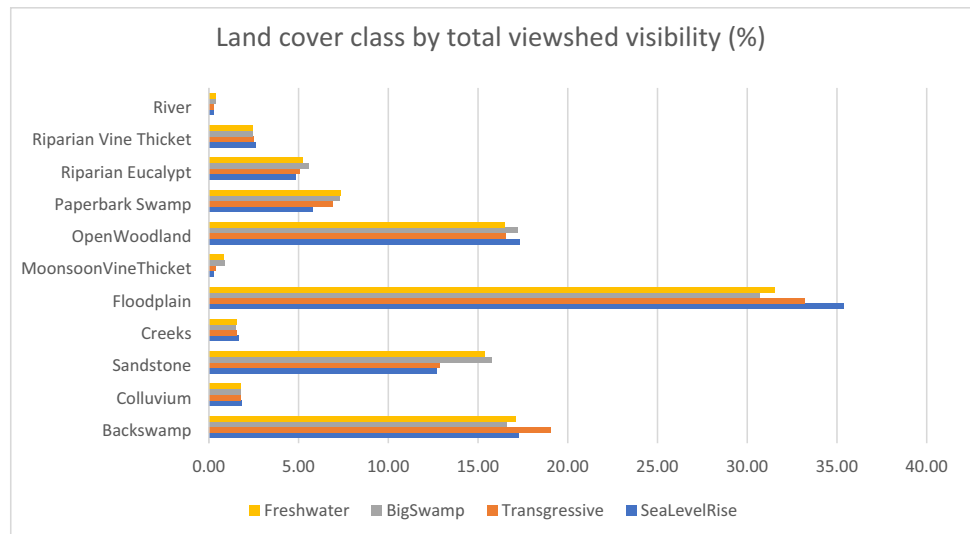


Fig. 11 Land cover class by total viewshed visibility as a percentage of environmental phase total visibility



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. Figure 13 displays these results.

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. 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 1,000 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. 2023). 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

Fig. 12 Land cover class by cumulative viewshed visibility as a percentage of environmental phase total visibility

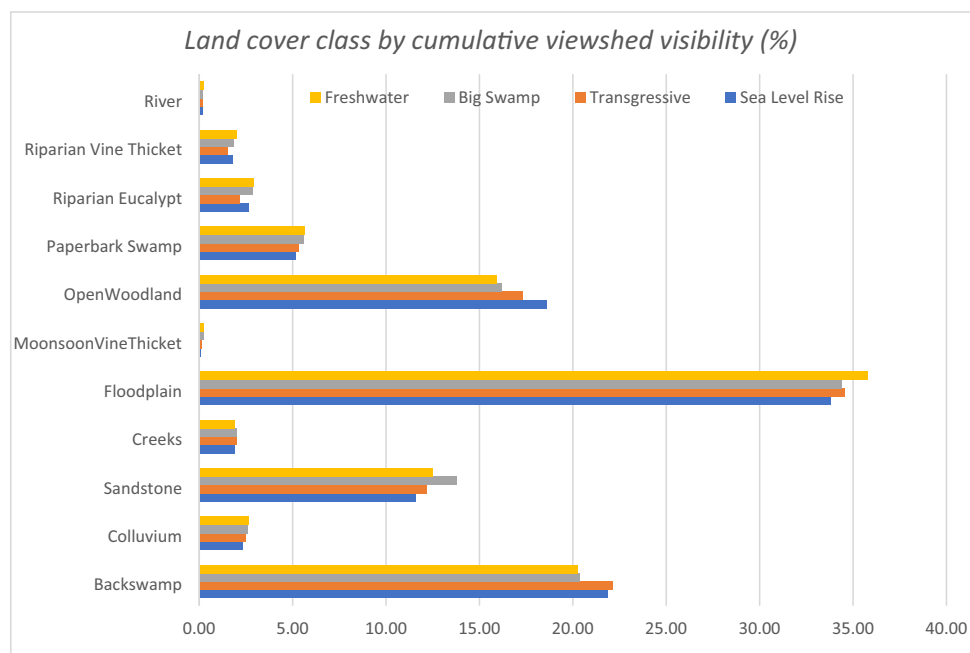
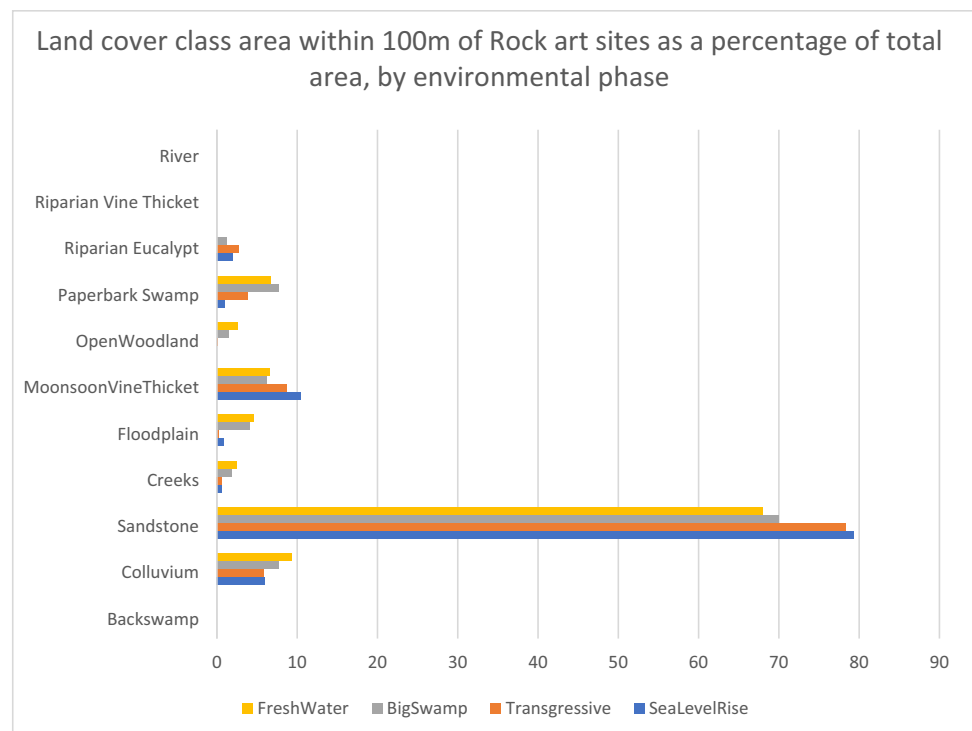


Fig. 13 Land cover class area within 100 m of rock art sites as a percentage of total area, by an environmental period



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 in the GRLLA during this phase (Kowlessar et al. 2023). The number of sites per phase shows the Big Swamp phase as 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 high frequency of sites during this time is sufficient to overcome the impact of differing 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 by 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. 2013, 2015, 2016; Wesley et al. 2017: 47; Woo 2020). This increase in site creation 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 creation coincides with a proliferation of artistic styles thought to be associated with changes to social structures, systems and boundaries as a result of 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 Fig. 4). The Big Swamp phase has the geographically widest geographic use of the sandstone plateau whilst the Freshwater phase has less use but maintains a broad distribution. This increased usage of sandstone plateau is also reflected in the increased percentage of sandstone found within 100 m of sites during these later phases (see Fig. 13). These results support an interpretation of the mobility changes during the flourishing mangal forests of the Big Swamp phase, which presumably encouraged 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 during Sea Level Rise and Transgressive phases.

The statistical tests which compared elevation levels of sites by phases (Fig. 6) showed a significant ($p < 0.05$)

difference between their elevation distributions, suggesting that sites of higher elevation were preferentially selected during Sea Level Rise and Transgressive 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 Transgressive 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 Transgressive 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 distribution of topographically elevated sites is unlikely to be the result of better preservation, 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 Fig. 7, 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. 2023; Wasson 1992; Woodroffe et al. 1985; 1989). 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 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 of 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, as opposed to views focused on the nearby floodplains on the east side

of East Alligator River which are dominant during the Big Swamp and Freshwater phases (see Fig. 5). 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 highest 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 Fig. 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 interaction points with new groups, perhaps facilitating trade, exchange and developing 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. 2023). Hunting strategies may

have also played a role in these changes in visibility focus, with vertebrates, such as macropods, representing significant portions of the diet during the earlier phases, before 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, 2015; Schrire 1982; Shine et al. 2013, 2015, 2016; 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 is 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 dominant in older diets (Allen and Barton 1989; Clarkson et al. 2017, 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 suggests 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. 2023). 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.

This research has focused on the presence or absence of a given style of art at each particular site within the dataset. This does not capture the number of motifs present of that style within each site nor does it capture microspatial characteristics of the motif arrangements within a given site. These factors do not impact the landscape context interpretations we have presented; however, they do present a future opportunity to further characterise the relationship between rock art practices and landscape context within the GRLLA.

Conclusion

This study takes a unique approach to rock art analysis in Northern Australia by combining paleogeographic modelling with the geostatistical analysis of rock art site placement and visibility. This approach has found statistically significant relationships between distinct rock art styles and site elevation. The relationship between site elevation and total visibility was shown to have only a weak correlation with no significance found in total land surface visibility between rock art classes. This demonstrates a nuanced connection between site placement and specific visible landscape contexts rather than overall visibility. This study has shown that when sites in the GRLLA are grouped by distinct chronological phases there are key changes over time in site selection based on what landscape is visible from the site of rock art inscriptions. As these key chronological phases of the rock art line up with known major changes in the local environment, this provides some important context to the economic and social changes occurring.

This shows a trend from a period of changing social complexity, where high elevations with tactical views of clan boundaries were initially preferred before a transition 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.

Author contributions All authors undertook fieldwork. J.K., M.W. and I.M. undertook data processing. J.K. wrote the main manuscript text and prepared figures. All authors reviewed the manuscript.

Funding 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) and an Australian Research Council Future Fellowship award (project number #FT220100184) funded by the Australian Government and a Flinders University Early Career Researchers Award. Thank you to the Njanjma Rangers who provided outstanding support for the research.

Declarations

Ethics approval This research was approved by Northern Land Council permit #79130 and via Flinders Human Research Ethics application #7704.

Competing interests The authors declare no competing interests.

References

- Acevedo A, Fiore D, Ferrari AA (2019) Rock art landscapes. A systematic study of images, topographies and visibility in south-central Patagonia (Argentina). *J Anthropol Archaeol* 56:101101
- Allen H (1989) Late pleistocene and Holocene settlement patterns and environment, Kakadu, Northern Territory, Australia. *Bull Indo-Pac Prehist Assoc* 9:92–117
- Allen H (1996) The time of the mangroves: Changes in mid-Holocene estuarine environments and subsistence in Australia and South-east Asia. *Bull Indo-Pac Prehist Assoc* 15:193–205
- Allen H, Barton G (1989) Ngarradj Warde Djokeng: white cockatoo dreaming and the prehistory of Kakadu. Oceania Publications, Sydney
- Blainey G (1975) The triumph of the nomads: a history of ancient Australia. The Macmillan Press, Netley
- Bourke PM (2004) Three Aboriginal shell mounds at Hope Inlet: evidence for coastal, not maritime Late Holocene economies on the Beagle Gulf mainland, northern Australia. *Aust Archaeol* 59(1):10–22
- Bradley R (1991) Rock art and the perception of landscape. *Camb Archaeol J* 1(1):77–101
- Bradley R (1997) Rock Art and the Prehistory of Atlantic Europe. Routledge, London
- Bradley R, Boado FC, Valcarce RF (1994a) Los petroglifos como forma de apropiación del espacio: algunos ejemplos gallegos. *Trab Prehist* 51(2):159–168
- Bradley R, Boado FC, Valcarce RF (1994b) Rock art research as landscape archaeology: a pilot study in Galicia, north-west Spain. *World Archaeol* 25(3):374–390
- Brandl E (1968) Aboriginal rock designs in beeswax and description of cave painting sites in western Arnhem Land. *Archaeol Phys Anthropol Ocean* 3(1):19–29
- Brockwell S (2006) Earth mounds in Northern Australia: a review. *Aust Archaeol* 63(1):47–56
- Brockwell S, Bourke P, Clarke A, Crassweller C, Faulkner P, Meehan B, O'Connor S, Sim R, Wesley D (2011) Holocene settlement of the northern coastal plains, Northern Territory, Australia. *Museums and Art Galleries of the Northern Territory*, vol. 27. <https://doi.org/10.3316/informit.820833577795709>
- Chaloupka G (1993) Journey in time: The world's longest continuing art tradition: the 50,000 year story of the Australian Aboriginal rock art of Arnhem Land. Reed Books, Chatswood
- Chippindale C, Taçon PS (1993) Two old painted panels from Kakadu: variation and sequence in Arnhem Land rock art. In: Steinbring J, Watchman A, Faulstich P, Taçon PSC (eds) Time and space: dating and spatial considerations in rock art research: papers of symposia F and E, Second AURA Congress, Cairns 1992. Australian Rock Art Research Association, Melbourne, pp 32–56
- Chippindale C, Taçon PS (1998) The many ways of dating Arnhem Land rock-art. In: Chippindale C, Taçon PS (eds) The archaeology of rock-art. Cambridge University Press, Cambridge, pp 90–111
- Chippindale C, Smith B, Taçon PSC (2000) Visions of dynamic power: archaic rock-paintings, altered states of consciousness and 'clever men' in Western Arnhem Land (NT). *Aust Camb Archaeol J* 10(1):63–101
- Clarkson C, Smith M, Marwick B, Fullagar R, Wallis LA, Faulkner P, Manne T, Hayes E, Roberts RG, Jacobs Z, Carah X, Lowe KM, Matthews J, Florin SA (2015) The archaeology, chronology and stratigraphy of Madjedbebe (Malakunanja II): a site in northern Australia with early occupation. *J Hum Evol* 83:46–64
- Clarkson C, Jacobs Z, Marwick B, Fullagar R, Wallis L, Smith M, Roberts RG, Hayes E, Lowe K, Carah X, Florin SA, McNeil J, Cox D, Arnold LJ, Hua Q, Huntley J, Brand HEA, Manne T, Fairbairn A, Shulmeister J, Lyle L, Salinas M, Page M, Connell K, Park G, Norman K, Murphy T, Pardoe C (2017) Human occupation of northern Australia by 65,000 years ago. *Nature* 547(7663):306–310
- Conkey MW (1980) The Identification of prehistoric hunter-gatherer aggregation sites: the case of Altamira. *Curr Anthropol* 21(5):609–630
- David B, Thomas J (2016) Handbook of landscape archaeology. Routledge, New York
- David B, Barker B, Petchey F, Delannoy J-J, Geneste J-M, Rowe C, Eccleston M, Lamb L, Whear R (2013) A 28,000 year old excavated painted rock from Nawarla Gabarnmang, northern Australia. *J Archaeol Sci* 40(5):2493–2501
- David B, Lamb L, Kaiwari J (2014) Landscapes of mobility: the flow of place. In: The Oxford handbook of the archaeology and anthropology of hunter-gatherers. Oxford University Press, Oxford, pp 1163–1190
- David B, Delannoy J-J, Gunn R, Brady LM, Petchey F, Mialanes J, Chalmers E, Geneste J-M, Moffat I, Aplin K (2017) Determining the age of paintings at JSARN-113/23, Jawoyn Country, central-western Arnhem Land plateau. *Archaeol Rock Art West Arnhem Land Aust* 47:371
- Díaz-Andreu M, Atiénzar GG, Benito CG, Mattioli T (2017) Do you hear what I see? Analyzing visibility and audibility in the rock art landscape of the Alicante mountains of Spain. *J Anthropol Res* 73(2):181–213
- Domingo Sanz I (2012) A theoretical approach to style in Levantine rock art. In: McDonald J, Veth P (eds) A companion to rock art. Wiley-Blackwell, Oxford, pp 306–321
- Domingo I, Smith C, Jackson G, Roman D (2020) Hidden sites, hidden images, hidden meanings: does the location and visibility of motifs and sites correlate to restricted or open access? *J Archaeol Method Theory* 27(3):699–722
- Fairén S (2010) Mobility, Visibility and the distribution of schematic rock art in Central-Mediterranean Iberia. In: Nicolucci F, Hermon S (eds) Proceedings of CAA2004, Prato 13–17 April 2004. CAA, Archaeolingua, pp 152–155
- Fairén-Jiménez S (2007) British Neolithic Rock Art in its Landscape. *J Field Archaeol* 32(3):283–295
- Finlayson C, Bailey B, Cowie I (1989) Macrophyte vegetation of the Magela Creek flood plain, Alligator Rivers Region
- Geoscience A (2015) Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid. Geoscience Australia. <https://doi.org/10.26186/89644>
- Guse DL (2005) Our home our country: a case study of law, land, and indigenous cultural heritage in the northern territory. Unpublished Master's Thesis, Charles Darwin University (Australia). ProQuest Dissertations & Theses Global, Ann Arbor
- Hartley R, Vawser AMW (1998) Spatial behaviour and learning in the prehistoric environment of the Colorado River drainage (southeastern Utah), western North America. In: Chippindale C, Taçon PSC (eds) The archaeology of rock-art. Cambridge University Press, Cambridge, pp 185–211
- Hiscock P (1996) Mobility and technology in the Kakadu coastal wetlands. *Bull Indo-Pac Prehist Assoc* 15:151–157
- Hiscock P (1999) Holocene coastal occupation of western Arnhem Land. In: Hall J, McNive I (eds) Australian coastal archaeology. Department of Archaeology and Natural History, Australian National University, Canberra, pp 91–103
- Hogarth PJ (2015) The Biology of Mangroves and Seagrasses. Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780198716549.001.0001>
- Intxaurbe I, Rivero O, Medina-Alcaide MÁ, Arriolabengoa M, Ríos-Garaizar J, Salazar S, Ruiz-López JF, Ortega-Martínez P, Garate

- D (2020) Hidden images in Atxurra Cave (Northern Spain): a new proposal for visibility analyses of Palaeolithic rock art in subterranean environments. *Quatern Int* 566–567:163–170
- Intxaurbe I, Arriolabengoa M, Medina-Alcaide MÁ, Rivero O, Rios-Garaizar J, Salazar S, Lfábano I, Garate D (2021) Quantifying accessibility to Palaeolithic rock art: Methodological proposal for the study of human transit in Atxurra Cave (Northern Spain). *J Archaeol Sci* 125:105271
- Intxaurbe I, Garate D, Arriolabengoa M, Medina-Alcaide MÁ (2022) Application of line of sight and potential audience analysis to unravel the spatial organization of palaeolithic cave art. *J Archaeol Method Theory* 29(4):1158–1189
- Johnston IG (2017) Body ornamentation in dynamic scenes: ritual and head-dresses in the Dynamic Figure rock art of western Arnhem Land, Australia. *Artefact: J Archaeol Anthropol Soc Victoria* 38:67–80
- Johnston IG (2018) The Dynamic Figure Art of Jabiluka: a study of ritual in early Australian rock art. Unpublished Thesis. The Australian National University, Canberra
- Johnston IG, Goldhahn J, May SK (2017) Dynamic Figures of Mirarr Country: Chaloupka's four-phase theory and the question of variability within a rock art style. In: David B, Taçon PSC, Delannoy JJ, Geneste JM (eds) *The Archaeology of Rock Art in Western Arnhem Land, Australia*. ANU Press, Canberra, pp 109–127
- Jones R (1985) *Archaeological research in Kakadu National Park*. Australian National Parks and Wildlife Special Publications 13, Canberra
- Jones T (2017) Disentangling the styles, sequences and antiquity of the early rock art of western Arnhem Land. Unpublished Unpublished PhD thesis Thesis. School of Culture, History and Language, College of Asia and the Pacific, The Australian National University, ANU
- Jones T, May SK (2017) Rock art and ritual function: the northern running figures of Western Arnhem land. *Artefact: J Archaeol Anthropol Soc Victoria* 38:53–66
- Jones T, Levchenko V, Wesley D (2017) How old is X-ray art? Minimum age determinations for early X-ray rock art from the 'Red Lily' (Wulk) Lagoon rock art precinct, western Arnhem Land. In: David B, Taçon PSC, Delannoy J-J, Geneste J-M (eds) *The Archaeology of Rock Art in Western Arnhem Land, Australia*, vol 47. ANU Press, Acton, p 129
- Jones T, Levchenko VA, King PL, Troitzsch U, Wesley D, Williams AA, Nayinggull A (2017b) Radiocarbon age constraints for a Pleistocene-Holocene transition rock art style: the Northern Running Figures of the East Alligator River region, western Arnhem Land, Australia. *J Archaeol Sci Rep* 11:80–89
- Jones T, Wesley D, May SK, Johnston IG, McFadden C, Taçon PS (2020) Rethinking the age and unity of large naturalistic animal forms in early Western Arnhem Land Rock Art, Australia. *Aust Archaeol* 86(3):238–252
- Kowlessar J, Keal J, Wesley D, Moffat I, Lawrence D, Weson A, Nayinggull A (2021) Reconstructing rock art chronology with transfer learning: a case study from Arnhem Land, Australia. *Aust Archaeol* 87(2):115–126
- Kowlessar J, Moffat I, Wesley D, Jones T, Maxime A, Willis MD, Nayinggull A, 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, Wilson AS (eds) *Visual Heritage*. Springer, Cham
- Kowlessar J, Moffat I, Wesley D, Willis M, Wrigglesworth S, Jones T, Nayinggull A, R. the Njanjma (2023) Reconstructing archaeological palaeolandscapes using geophysical and geomatic survey techniques: an example from Red Lily Lagoon, Arnhem Land, Australia. *PLOS ONE* 18(5):e0283006
- Lewis D (1997) Bradshaws: the view from Arnhem Land. *Australian Archaeology* 44(1):1–16
- Lewis D (1988) *The Rock paintings of Arnhem Land*. B.A.R., Oxford
- Llobera M (2003) Extending GIS-based visual analysis: the concept of visualsapes. *Int J Geogr Inf Sci* 17(1):25–48
- May SK, Johnston IG, Taçon PS, Sanz ID, Goldhahn J (2018) Early Australian Anthropomorphs: Jabiluka's dynamic figure rock paintings. *Camb Archaeol J* 28(1):67–83
- McDonald J (2005) Archaic faces to headresses: the changing role of rock art across the Arid Zone. In: Veth P, Smith M, Hiscock P (eds) *Desert Peoples: Archaeological Perspectives*. Blackwell, Oxford, pp 116–141. <https://doi.org/10.1002/9780470774632.ch7>
- McDonald J (2017) Discontinuities in arid zone rock art: graphic indicators for changing social complexity across space and through time. *J Anthropol Archaeol* 46:53–67
- McDonald J, Veth P (2006) Rock art and social identity: a comparison of Holocene graphic systems in arid and fertile environments. In: Lilley I (ed) *Archaeology of Oceania: Australia and the Pacific Islands*. Blackwell, Oxford, pp 96–115
- McDonald J, Veth P (2012) The social dynamics of aggregation and dispersal in the western desert. In: McDonald J, Veth P (eds) *A companion to rock art*. Blackwell Publishing, Oxford, pp 90–102
- Morwood MJ, Hobbs DR (1995) Themes in the prehistory of tropical Australia. *Antiquity* 69(265):747–768
- Needham R (1984) *Alligator Rivers, Northern Territory: 1: 250,000 Geological Series Explanatory Notes*. Department of National Resources, Bureau of Mineral Resources, Geology and Geophysics
- Norman K, Bradshaw CJA, Saltré F, Clarkson C, Cohen TJ, Hiscock P, Jones T, Boesl F (2024) Sea level rise drowned a vast habitable area of north-western Australia driving long-term cultural change. *Quat Sci Rev* 324:108418. <https://doi.org/10.1016/j.quascirev.2023.108418>
- Reeves JM, Barrows TT, Cohen TJ, Kiem AS, Bostock HC, Fitzsimmons KE, Jansen JD, Kemp J, Krause C, Petherick L, Phipps SJ (2013a) Climate variability over the last 35,000 years recorded in marine and terrestrial archives in the Australian region: an OZ-INTIMATE compilation. *Quatern Sci Rev* 74:21–34
- Reeves JM, Bostock HC, Ayliffe LK, Barrows TT, De Deckker P, Devriendt LS, Dunbar GB, Drysdale RN, Fitzsimmons KE, Gagan MK, Griffiths ML, Haberle SG, Jansen JD, Krause C, Lewis S, McGregor HV, Mooney SD, Moss P, Nanson GC, Purcell A, van der Kaars S (2013b) Palaeoenvironmental change in tropical Australasia over the last 30,000 years – a synthesis by the OZ-INTIMATE group. *Quatern Sci Rev* 74:97–114
- Ross J, Davidson I (2006) Rock Art and Ritual: An Archaeological Analysis of Rock Art in Arid Central Australia. *J Archaeol Method Theory* 13(4):304–340
- Ruiz MF, Gadella FC, Alejos AD, Spanedda L (2021) Approaches to visibility and strategical control of the Sierra Harana Schematic Rock Art (Granada, Spain). *de Prehistoria y Arqueología* 31:27–44
- Schaafsma P (1985) Form, content, and function: theory and method in North American rock art studies. *Adv Archeol Method Theory* 8:237–277
- Schrire C (1982) *The Alligator Rivers: Prehistory and Ecology in Western Arnhem Land*. Terra Australis 7, Canberra
- Senior B, Smart P (1976) *Coburg Peninsula: Melville Island, Northern Territory 1: 250,000 Geological Series Explanatory Notes*. Department of National Resources, Bureau of Mineral Resources, Geology and Geophysics
- Shine D, Wright D, Denham T, Aplin K, Hiscock P, Parker K, Walton R (2013) Birriwilk rockshelter: a mid-to late Holocene site in ManilkarrCountry, southwest Arnhem Land, Northern Territory. *Austral Archaeol* 76(1):69–78
- Shine D, Marshal M, Wright D, Denham T, Hiscock P, Jacobsen G, S. S. (2015) The archaeology of Bindjarran rockshelter in Manilkarr Country, Kakadu National Park, Northern Territory. *Aust Archaeol* 80:104–111

- Shine D, Hiscock P, Denham T (2016) The archaeology of Ingaanjal-wurr rockshelter in Manilkarr Country, western Arnhem Land. *Aust Archaeol* 82(1):67–75
- Singh NU, Roy A, Tripathi A, Test C-S, Test B, Test O-S K-S, Mann-Whitney U, Run W-W, Kruskal-Wallis H, Cochran's Q (2013) Non parametric tests: hands on SPSS. ICAR Research Complex for NEH Region, Umiam, Meghalaya
- Smith CE (1994) Situating style: an ethnoarchaeological study of social and material context in an Australian Aboriginal artistic system. Unpublished Thesis, University of New England. Armidale
- Sweet I, Brakel A, Carson L (1999) The Kombolgie Subgroup—a new look at an old 'formation.' *J Earth Sci* 45(219):232
- Taçon P, Chippindale C (1994) Australia's ancient warriors: changing depictions of fighting in the rock art of Arnhem Land, NT. *Camb Archaeol J* 4(2):211–248
- Taçon PSC (1989a) From Rainbow Snakes to 'X-Ray' Fish: the nature of the recent rock painting tradition of Western Arnhem Land, Australia. Unpublished Thesis. Faculty of Arts, Australian National University. Canberra
- Taçon PSC (1989) From the "Dreamtime" to the present: the changing role of Aboriginal Rock Paintings in Western Arnhem Land Australia. *Can J Native Stud* 4(2):317–339
- Taçon PSC (1993) Regionalism in the recent rock art of Western Arnhem Land, Northern Territory. *Archaeol Ocean* 28(3):112–120
- Taçon PS, Brockwell S (1995) Arnhem Land prehistory in landscape, stone and paint. *Antiquity* 69(265):676–695
- Taçon PSC, May SK, Lamilami R, McKeague F, Johnston IG, Jalandoni A, Wesley D, Sanz ID, Brady LM, Wright D, Goldhahn J (2020) Maliwawa figures—a previously undescribed Arnhem Land rock art style. *Aust Archaeol* 86(3):208–225
- Taylor L (1996) *Seeing the Inside*. Oxford University Press, New York
- Taylor L (2008a) Negotiating form in Kuninjku Bark-paintings [Other Journal Article]. *Austral Aborig Stud* (Canberra) 1:56–66
- Taylor L (2008b) 'They may say tourist, may say truly painting': aesthetic evaluation and meaning of bark paintings in western Arnhem Land, northern Australia. *J Roy Anthropol Inst* 14(4):865–885
- Taylor J, Dunlop C (1985) Plant communities of the wet-dry tropics of Australia: the Alligator Rivers region, Northern Territory. *Proc Ecol Soc Aust* 13:127
- Tilley C (1994) *A Phenomenology of Landscape*. Berg, Oxford
- Veth P (1989) Islands in the interior: a model for the colonization of Australia's arid zone. *Archaeol Ocean* 24(3):81–92
- Veth P, Harper S, Ditchfield K, Ouzman S, B. A. Corporation (2021) The case for continuity of human occupation and rock art production in the Kimberly, Australia. In: McGrath A, Russell L (eds) *The Routledge companion to global indigenous history*, pp 194–220
- Wasson R (Ed) (1992) Modern sedimentation and late quaternary evolution of the Magela Creek Plain. Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra, Canberra
- Wesley D (2016) *Urrmarning: Red Lily Lagoon Rock Art Project*. George Chaloupka Fellowship Report 2010–2011. Unpublished report to the Museum and Art Gallery of the Northern Territory
- Wesley D, Jones T, Whitau R (2017) People and fish: late Holocene rock art at Wulk Lagoon, Arnhem Land. In: David B, Taçon PSC, Delannoy JJ, Geneste JM (eds) *The Archaeology of Rock Art in Western Arnhem Land, Australia*, vol 47. ANU Press, Canberra, pp 21–50
- Wheatley D (1995) Cumulative viewshed analysis: a GIS-based method for investigating intervisibility, and its archaeological application. In: Lock GR, Stancic G (eds) *Archaeology And Geographic Information Systems: A European Perspective*. Taylor and Francis, London, pp 171–186
- Wheatley D, Gillings M (2000) Vision, perception and GIS: developing enriched approaches to the study of archaeological visibility. In: Lock GR (ed) *Beyond the map: archaeology and spatial technologies*. IOS Press, Amsterdam, pp 1–27
- Whitley DS (1998) Finding rain in the desert: landscape, gender and far western Nother American rock-art. In: Chippindale C, Taçon PSC (eds) *The archaeology of rock-art*. Cambridge University Press, Cambridge
- Wiessner P (1984) Reconsidering the behavioral basis for style: a case study among the Kalahari San. *J Anthropol Archaeol* 3(3):190–234
- Wiessner P (1989) Style and changing relations between individual and society. In: Hodder I (ed) *The Meanings of Things: Material Culture and Symbolic Expression*. Unwin Hyman, London, pp 56–63
- Wiessner P (1990) Is there a unity to style? In: Conkey M, Hastorf C (eds) *The Uses of Style in Archaeology*. Cambridge University Press, Cambridge
- Williams AN, Ulm S, Sapienza T, Lewis S, Turney CSM (2018) Sea-level change and demography during the last glacial termination and early Holocene across the Australian continent. *Quatern Sci Rev* 182:144–154
- Wilson B, Brocklehurst P, Clark M, Dickinson K (1990a) Vegetation survey of the Northern Territory, Australia: explanatory notes to accompany 1: 1 000 000 map sheets. Conservation Commission of the Northern Territory
- Wilson B, Brocklehurst P, Whitehead PJ (1990b) Classification, distribution and environmental relationships of coastal floodplain vegetation, Northern Territory, Australia, March-May 1990. Conservation Commission of the Northern Territory
- Wobst HM (1977) Stylistic behavior and information exchange. In: Cleland CE (ed) *For the Director: Research Essays in Honor of James B. Griffin*. Museum of Anthropology, University of Michigan, Ann Arbor, pp 317–342
- Woo KGP (2020) *Shifting Palaeoeconomies in the East Alligator River Region: An Archaeomalacological Analysis*. Unpublished Thesis. Department of Archaeology, School of Philosophical and Historical Inquiry, Faculty of Arts and Social Sciences, The University of Sydney
- Woodroffe CD (1993) Late quaternary evolution of coastal and lowland riverine plains of Southeast Asia and northern Australia: an overview. *Sed Geol* 83(3):163–175
- Woodroffe CD (1988) Changing mangrove and wetland habitats over the last 8000 years, northern Australia and Southeast Asia. In: Wade-Marshall D, Loveday P (eds) *Northern Australia: Progress and Prospects Volume 2: floodplain research*. North Australia Research Unit, Australian National University, Darwin, pp 1–33
- Woodroffe CD, Thom BG, Chappell J (1985) Development of widespread mangrove swamps in mid-Holocene times in northern Australia. *Nature* 317(6039):711–713
- Woodroffe CD, Chappell J, Thom BG, Wallensky E (1989) Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology* 36(5):737–756
- Woodroffe CD, Chappell JMA, Thom BG, Wallensky E (1986) Geomorphological Dynamics and Evolution of the South Alligator Tidal River and Plains, Northern Territory. Mangrove Monograph No. 3. Australian National University North Australia Research Unit, Darwin
- Yokoyama Y, De Deckker P, Lambeck K, Johnston P, Fifield LK (2001) Sea-level at the Last Glacial Maximum: evidence from north-western Australia to constrain ice volumes for oxygen isotope stage 2. *Palaeogeogr Palaeoclimatol Palaeoecol* 165(3):281–297

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.