Archaeological Prospection
Archaeol. Prospect. **24**, 169–179 (2017)

(wileyonlinelibrary.com) DOI: 10.1002/arp.1567

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

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

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

Introduction

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

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

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Received 31 October 2016
Revised 4 December 2016
Accepted 18 December 2016

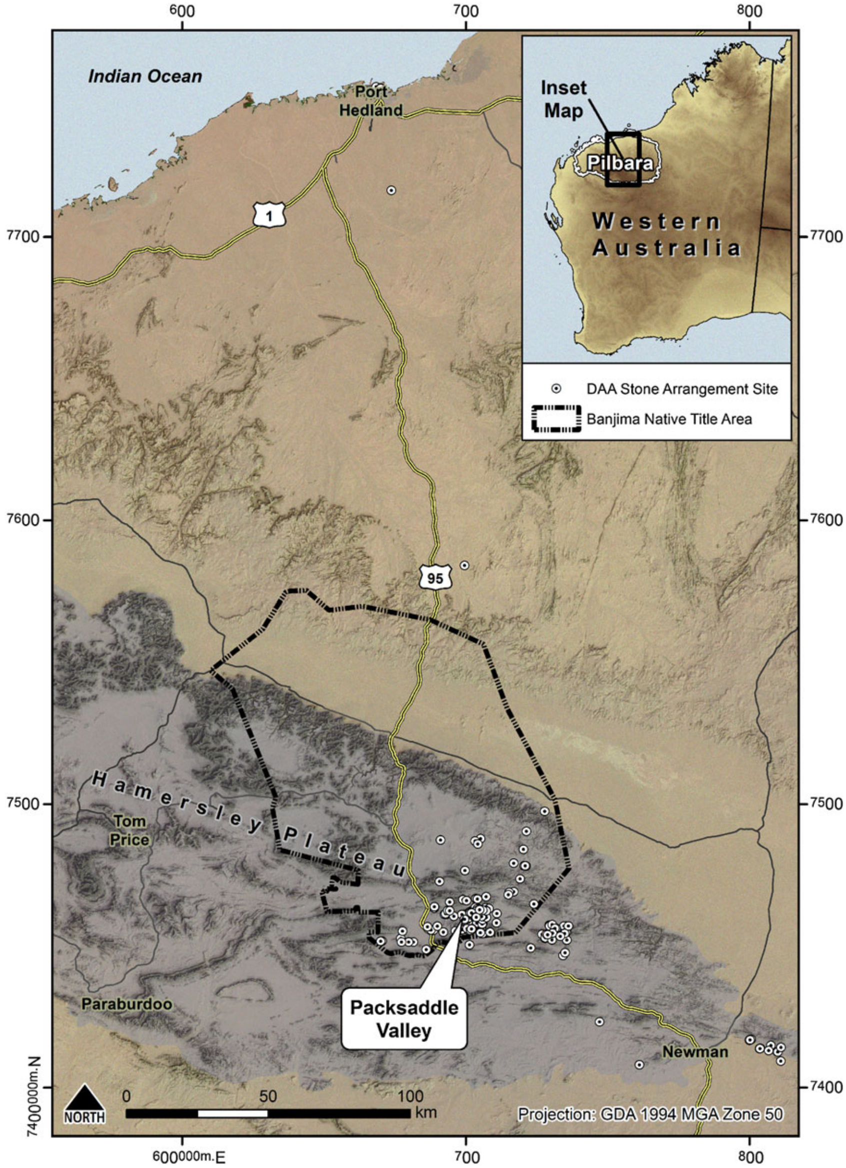

Figure 1. Regional overview map with major geographic features, Department of Aboriginal Affairs (DAA) registered stone arrangement sites, cultural areas, and the approximate position of the Packsaddle Valley, Pilbara region of Western Australia. [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

DOI: 10.1002/arp

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

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

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

The Packsaddle Valley study area

Environmental setting

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

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

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

Stone arrangements

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

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

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

DOI: 10.1002/arp

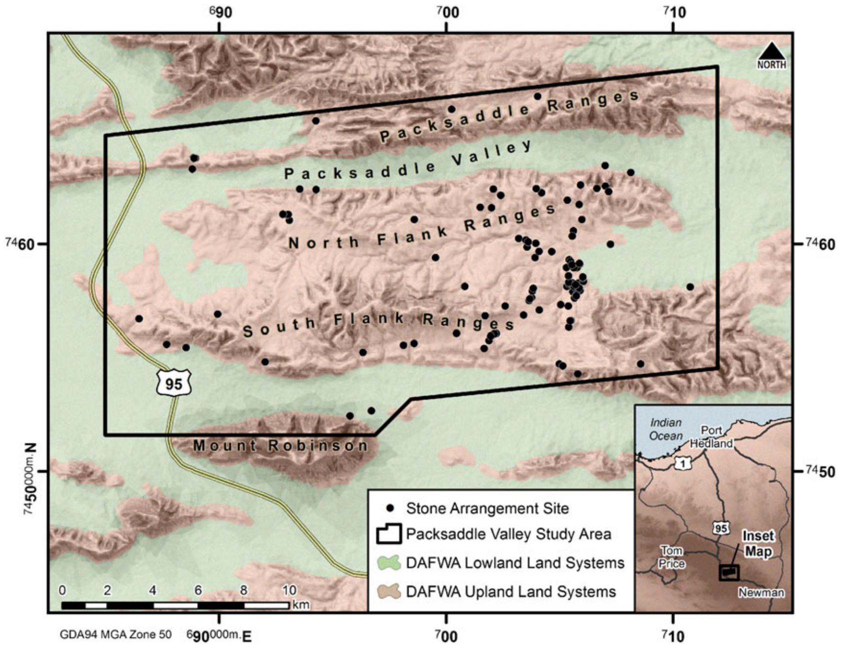

Figure 2. Packsaddle Valley study area map and land system classes, including locations of stone arrangement sites. [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

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

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

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

DOI: 10.1002/arp

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

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

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

Materials and methods

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

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

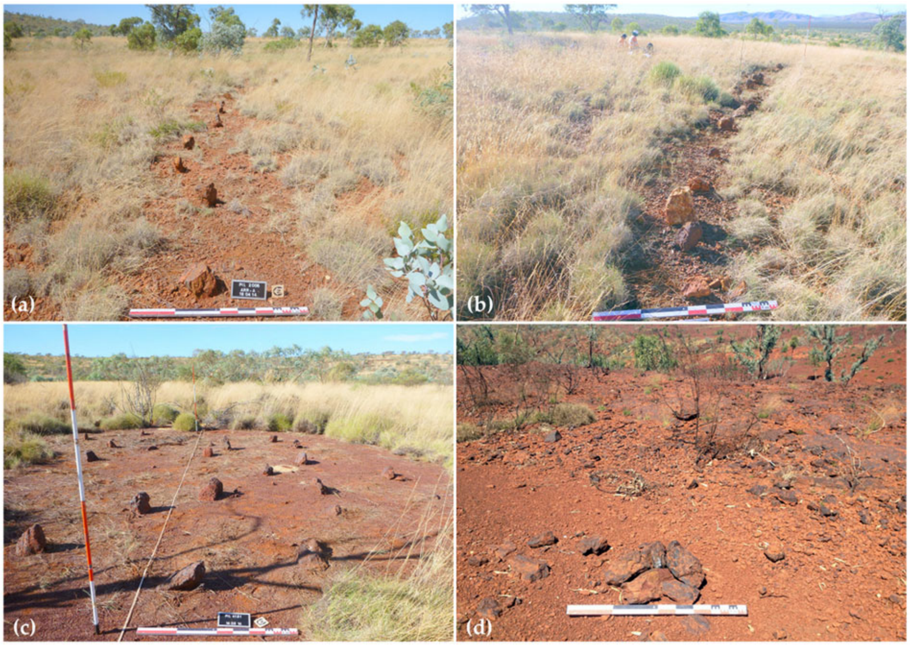

Figure 3. Examples of Packsaddle Valley stone arrangement design types. Generalized design categories include (a) linear, (b) curvilinear, (c) amorphous, and (d) cairn (Photographs: J. Brindley). Variations in design type categories are common regionally. [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

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

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

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

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

Table 2. Topographic slope position classification criteria.

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

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

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

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

[a] Land redevelopments preclude definitive classification due to infrastructure and altered natural ground surfaces.

Results

The resulting digital terrain model of topographic slope position classes, with stone arrangement site locations is presented in Figure 4. Figure 4 demonstrates that stone arrangement locations are highly correlated with upper topographic slope positions. The extracted raster values presented in Table 3 indicate 85.6% of stone arrangement sites occur in upper topographic contexts, with stone arrangements observed on the summit/hilltop/ridges (38.5%), upper slopes (16.3%), midslopes (15.4%), and flat upland ground surfaces

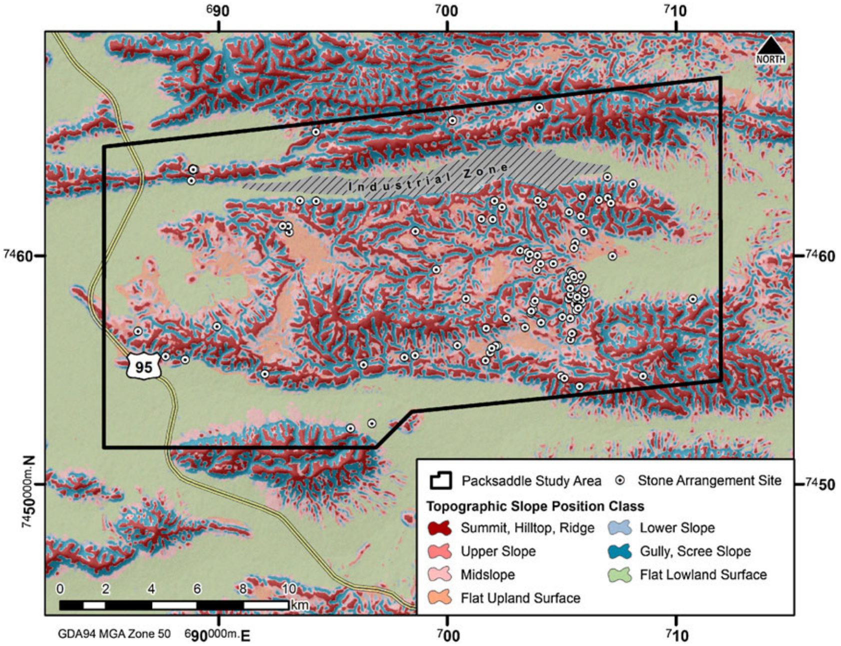

Figure 4. Topographic slope position classes for the Packsaddle Valley study area.

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

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

[a] Note the total classified land area is 349.3 km^2, as the industrial zone in Table 3 precludes classification of 15.1 km^2.

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

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

Discussion

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

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

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

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

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

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

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

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

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

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

Conclusions

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

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

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

Acknowledgments

The authors wish to acknowledge the Banjima Native Title Claimants as the Traditional Owners of the land this study encompasses. The authors sincerely thank the Banjima community and Karijini Developments Pty Ltd for their support and involvement with the field investigations. The authors additionally appreciate the thoughtful and productive comments of the two anonymous reviewers. This project was completed with the assistance of BHP Billiton Iron Ore (BHPBIO) Pty Ltd, and the authors thank the BHPBIO Heritage and GIS Department, especially Dr Jade Pervan, Daniel Bruckner, Paul Berry, Annunziata Strano, Ross Stanger, Simon Trinder, and Roger Gregory for facilitating access to spatial data and site reports. Additional field staff the authors wish to recognize are Allan Ewen, Paul Taylor, Zaine Hollister, and Peter Sweeny. Aside from the authors, the Scarp Archaeology Pty Ltd team actively involved with stone arrangement recording includes Jared Brindley, Amy Stevens, Rachel Bulloch, and Helen Selimiotis. The remote sensing and spatial components of this research additionally benefited from conversations with the University of Adelaide's Spatial Information Group. Funds for the online publication of this article were provided by the University of Adelaide, in support of W.B.L.'s PhD Candidature.

Author contributions

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

Declaration of interest statement

The authors declare no conflict of interest.

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