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Determining the boundaries, structure and volume of buried shell matrix deposits using ground-penetrating radar: A case study from northern Australia

Selene L. Kenady[a,*], Kelsey M. Lowe[b,d], Sean Ulm[a,c]

[a] College of Arts, Society and Education, James Cook University, PO Box 6811, Cairns, QLD 4870, Australia
[b] Institute of Resilient Regions, School of Arts and Communication, The University of Southern Queensland, Toowoomba, QLD 4350, Australia
[c] ARC Centre of Excellence for Australian Biodiversity and Heritage, James Cook University, PO Box 6811, Cairns, QLD 4870, Australia
[d] School of Social Science, The University of Queensland, Brisbane, QLD 4872, Australia

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ABSTRACT

Ground-penetrating radar (GPR) is used in this study to delineate the extent and internal structure of a large late Holocene buried shell matrix site at Thundiy, Bentinck Island, northern Australia. Shell matrix sites comprise a key component of the coastal archaeological record. The extensive nature of many shell matrix sites presents challenges for archaeological sampling regimes. While large-scale excavation is undesirable and impractical, limited test pits often represent only a tiny fraction of large shell deposits and are rarely considered representative. This study transforms GPR data into three-dimensional models which form the basis of deposit volume estimates. Volume estimates are evaluated against excavation data to test their accuracy. Results demonstrate that this novel methodology can generate accurate three-dimensional representations of buried shell matrices and highly accurate volume estimations with error margins of 3.5% ± 7%. It is recommended, though, that more inclusive error margins of 19.5% ± 17% are used to account for potential error, especially where results cannot be verified. This greater understanding of the extent and structural variability of deposits can be utilised to create robust sampling strategies for excavation. The methodology could also be further employed to enhance comparative regional studies and to add to conservation and management practices of buried shell matrix sites. If applied more widely this methodology will not only benefit our understanding of shell matrix deposits but also the wider archaeological record of coastal regions worldwide.

1. Introduction

Shell middens are a significant component of the coastal archaeological record, but they are notoriously difficult to study. Shell matrix sites are often large and structurally heterogeneous with complex formation histories. For large stratified shell matrix sites the majority of the deposits are buried making the design of appropriate and representative sampling regimes challenging. Without total excavation the population from which the sample was taken will never be fully understood. This study addresses these challenges by employing ground-penetrating radar (GPR) to map the structure and boundaries of buried shell matrix deposits, then transforming these survey results into three-dimensional models and volume estimates. This study establishes the specific methods for transforming GPR data into volume estimates and three-dimensional (3D) models, and tests the accuracy of these models and estimates against data generated via excavation. This methodology allows for characterisation of the size and shape of buried matrices, creating a better understanding of the population from which samples are drawn without requiring extensive excavation. The methodology also has implications for conservation efforts such as cultural heritage and community-based management plans; by creating a better understanding of buried sites without destroying the archaeological record in the process.

2. Background

There has been limited research bringing quantitative approaches to sampling issues in shell matrix research. O'Neil (1993), Poteate and Fitzpatrick (2013), and Treganza and Cook (1948) all excavated large proportions of shell matrix sites to establish the sampling size and strategy required to produce an accurate understanding of the population of the entire matrix. Bailey (1975) and Greenwood (1961)

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* Corresponding author.
E-mail address: selene.kenady@my.jcu.edu.au (S.L. Kenady).

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focused on how much excavated shell material was needed to be analysed in detail to characterise the overall sample accurately. The results of these studies varied significantly, illustrating just how difficult it is to create sampling regimes which appropriately characterise shell matrix sites, and how different research aims can have a significant impact on what constitutes an ‘appropriate’ sample. All of the studies emphasised that the samples they found necessary to accurately characterise the site being examined were not necessarily suitable for other sites. These prior approaches do not create a secure basis for addressing sampling issues in shell matrix research; this study suggests new approaches need to be established.

The most significant challenge in designing appropriate sampling regimes is in understanding the full scope of the buried matrix. Only three studies have attempted to calculate the total volume of buried shell matrix deposits (Shenkel, 1986; Sorant and Shenkel, 1984; Treganza and Cook, 1948), but these studies failed to determine the extent of the buried deposits without full excavation. Total excavation of shell matrix sites is undesirable both in terms of expenditure and destruction of the archaeological record. However, the issue of establishing buried deposit boundaries without total excavation can be addressed via the exploratory capabilities of geophysical surveys.

To date there have been few applications of geophysical surveys in shell matrix research. An extensive literature review of the application of geophysical surveys to the investigation of shell matrix sites found only 23 papers (Table 1) representing 17 case studies (three of the case studies were represented in multiple published papers). These 23 articles included three geological studies (Dougherty and Dickson, 2012; Neal et al., 2002; Weill et al., 2012) and 14 archaeological case studies. The geophysical methods employed included GPR, magnetometry, electrical resistivity, magnetic susceptibility, seismic refraction, electromagnetic induction (EM) and terrestrial laser scanning (TLS). While multiple studies addressed locating buried shell deposits, features within the deposits and site formation, none used the geophysical methods to create three-dimensional models of the deposits and only the Larsen et al. (2017) study quantified the deposits. However, to quantify the deposits Larsen et al. (2017) utilised TLS (also called terrestrial LiDAR) which is limited, in that it cannot differentiate between shell matrices and surrounding deposits nor can it characterise buried deposits; only the mounded matrix above the surrounding ground plane.

Beyond shell matrix research, there have been efforts to create volume estimates for buried matrices from geophysical survey results. However, only one of these can be tied to archaeological research (Kristiansen, 2013). The current study found the processing steps detailed by Kristiansen (2013) to be an invaluable insight into how to transform geophysical data into volume estimates and 3D models in ArcGIS. Kristiansen's methods were used as the basis for the methods employed in this study (detailed in Section 3.5) which were then altered and expanded where required.

Table 2
Breakdown by geophysical technique of papers utilising geophysical surveys to create volume estimates.

Publication	Geological medium	GPR	Electrical res.	TLS
Ai et al. (2014)	Glacier ice	x		
Baojuan et al. (2015)	Glacier ice	x		
Binder et al. (2009)	Glacier ice	x		
Colucci et al. (2015)	Glacier ice	x		
Dickson et al. (2009)	Beach sand	x		
Kristiansen (2013)	Perennial snow patch	x		
Larsen et al. (2017)	Shell matrix			x
Navarro et al. (2014)	Glacier ice	x		
Nowroozi et al. (1997)	Gravel deposits		x	
Prinz et al. (2011)	Glacier ice	x		
Rucker et al. (2011)	Dredgable river sediments		x	
Sambuelli and Bava (2012)	Lake water	x		
Tetegan et al. (2012)	Rock fragments		x	
Van Heteren et al. (1996)	Beach sand	x		
Wang et al. (2014)	Glacier ice	x		
Yde et al. (2014)	Glacier ice	x		

Aside from the paper by Larsen et al. (2017) employing TLS these volume estimate studies have all employed GPR and electrical resistivity (Table 2). Of the papers reviewed, only four studies verified the results via independent methods while only seven provided error margins on their estimations (with two of the papers doing both). Navarro et al. (2014) present one of the most thorough error estimations, from which they concluded that the error margin on the volume estimates for the glaciers studied amounted to 4–8% of the total volume. Baojuan et al. (2015) and Wang et al. (2014) examined system error and determined low ranges (1.18% and 1.2–5% respectively). Ai et al. (2014) and Binder et al. (2009) both reported significant errors

Table 1
Summary of geophysical studies investigating shell matrix sites, by geophysical technique.

Publication	Magnetometry	Magnetic susc.	EM	GPR	Electrical res.	Other
Arias et al. (2017)	x					
Arnold et al. (1997)	x			x		
Bērziņš et al. (2014)	x			x		
Chadwick and Madsen (2000)				x		
Connah et al. (1976)	x	x				
Dalan et al. (1992)	x				x	x (Seismic refraction)
Dougherty and Dickson (2012)				x		
Larsen et al. (2017)						x (TLS)
Lowe (2010)					x	
Moffat et al. (2008)	x		x			
Neal et al. (2002)				x		
Pluckhahn et al. (2009)				x	x	
Pluckhahn et al. (2010)				x	x	
Pluckhahn et al. (2016)				x		
Rodrigues et al. (2009)			x	x		
Rodrigues et al. (2015)				x		
Rosendahl et al. (2014)		x				
Santos et al. (2009)			x			
Thompson (2007)					x	
Thompson and Andrus (2011)					x	
Thompson and Pluckhahn (2010)				x	x	
Thompson et al. (2004)	x		x	x	x	
Weill et al. (2012)				x		