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**Extended Residence Times for Foraminifera in a Marine-Influenced Terrestrial Archaeological Deposit and Implications for Palaeoenvironmental Reconstruction**

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## Abstract

Accelerator Mass Spectrometry (AMS) radiocarbon dating and taphonomic grading was undertaken on foraminifera preserved in the archaeological shell matrix site of Thundi, Bentinck Island, southern Gulf of Carpentaria, Australia. Foraminifera were assigned to one of six taphonomic grades ranging from pristine to severely abraded. AMS dating demonstrates a weak relationship between preservation status and age. Foraminifera ages are inconsistent with multiple ages on marine shell from the same deposit implying significant sediment transport system residence ages (the time between death of the organism and final deposition) for foraminifera in the deposit. Results demonstrate that foraminifera cannot be assumed to be contemporary with other components of the sedimentary context in which they occur, indicating that caution is required in interpreting chronologies and palaeoenvironmental records based on foraminifera recovered from highly dynamic depositional settings. Findings point to the potential of foraminifera AMS dating of coastal archaeological deposits to contribute to evaluations of site integrity and chrono-stratigraphic analyses.

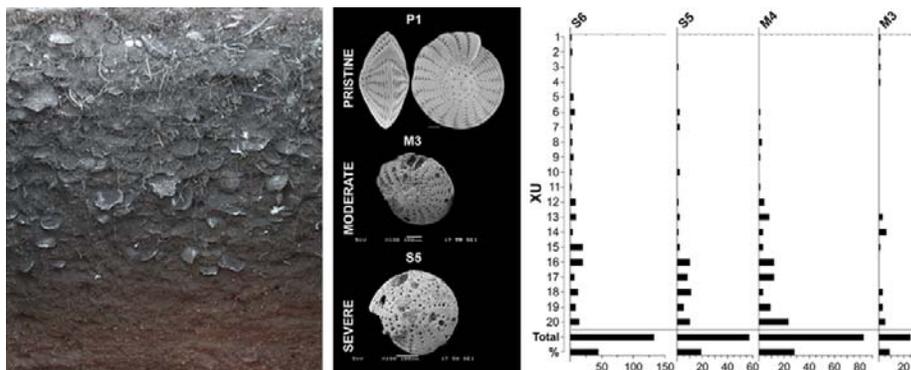
## Keywords

foraminifera; taphonomy; site formation processes; shell midden; palaeoenvironmental reconstruction; AMS radiocarbon dating; microfauna

## Highlights

- Foraminifera were studied in a marine-influenced archaeological deposit
- Foraminifera were assigned to taphonomic grades from pristine to severely abraded
- AMS ages demonstrate weak relationship between preservation status and age
- Results point to significant residence ages for foraminifera
- Foraminifera cannot be assumed to be contemporary with other site components

## Graphical Abstract



## 1. Introduction

Coastal archaeological deposits adjacent to nearshore environments are subject to highly dynamic processes that shape their formation and post-depositional alteration. Sea-level change, storm events and human and non-human impacts create multiple vectors differentially impacting coastal deposits during and after their deposition (Bird 1992; Rowland and Ulm 2012; Szabó 2012). To understand the numerous site formation processes impacting coastal shell deposits and to develop an understanding of site integrity, archaeologists conventionally employ stratigraphic analyses, shell taphonomy studies, shell taxa analysis, intra-specific size analysis and shell fragmentation studies (e.g. Attenbrow 1992; Bailey 1983; Carter et al. 1999; Claassen 1998; Hughes and Sullivan 1974; O'Connor and Sullivan 1994; Rick et al. 2006; Ulm 2006). The potential of microfauna, such as foraminifera, to address these questions has rarely been considered (cf. Reitz and Shackley 2012).

Foraminifera are single-celled organisms (amoeboid protists), abundant in marine environments, that secrete a hard calcium carbonate shell or 'test'. Foraminifera are routinely used in earth and oceanographic sciences for palaeoenvironmental reconstructions and directly dated to constrain depositional sequences, contributing to studies of sea-level change, climate change, reef-island accretion, sediment transport dynamics and intertidal zonation (e.g. Callard et al. 2011; Dawson et al. 2014; Ford and Kench 2012; Gehrels et al. 2012; Herkat and Ladjal 2013; Koutavas et al. 2002; Reymond et al. 2013; Sarnthein et al. 2015; Woodroffe and Morrison 2001; Woodroffe et al. 2007; Woodroffe 2009; Woodroffe et al. 2005; Yamano et al. 2000). However, foraminifera are rarely used in archaeological applications (cf. Lilley et al. 1999; McNiven 1996; Rosendahl et al. 2007, 2014; Weisler 1999; Weisler et al. 2012), despite their potential to contribute to understandings of coastal archaeological site formation processes and palaeoenvironments.

As foraminifera are ubiquitous in marine environments, natural terrestrial deposits created, redeposited or otherwise impacted by marine action and events (e.g. tides, storm surges etc) should exhibit foraminifera. In contrast, sites formed by cultural processes with no natural marine depositional processes influencing their formation, should contain very few, if any, foraminifera (McNiven 1996; Rosendahl et al. 2007). On this basis, foraminiferal density studies have been established as a reliable criterion for distinguishing between natural and cultural marine shell deposits (Rosendahl et al. 2007, 2014); however, the wider potential of foraminiferal analyses to contribute to understandings of foraminifera transport and depositional processes in archaeological contexts remains undeveloped. This study applies AMS radiocarbon dating and a novel taphonomic classification of foraminifera to refine understandings of site formation processes at the archaeological shell midden site of Thundiy, Bentinck Island, southern Gulf of Carpentaria. We provide a taphonomic classification of foraminifera related to the complex taphonomic histories of these tests rather than age, providing the basis for assessing the chronology and taphonomic characteristics of the foraminifera assemblage. Results call into question the validity of using foraminifera as tools for chronology-building and defining environmental characteristics in palaeoenvironmental reconstruction in highly dynamic depositional settings.

## 2. Background

Recent studies have employed AMS dating of biogenic carbonate sand grains to investigate the contribution of benthic foraminifera to reef-island accretion and to determine the depositional chronology of reef-island sand cays in the Pacific (Dawson et al. 2014; Woodroffe and Morrison 2001; Woodroffe et al. 2007). These studies emphasise the importance of dating individual foraminifera that have undergone rapid transport from

their source to the site of deposition to ensure that ages reflect the time of deposition with negligible residence times (the time lag between sediment production and either final deposition or permanent loss; see Dawson et al. 2014:69) and post-depositional reworking. 'Pristine' foraminifera tests (i.e. those assumed to have been rapidly deposited after death as indicated by morphological attributes) are preferentially selected for dating to reduce potential post-depositional age bias (Dawson et al. 2014; Woodroffe et al. 2007). For instance, Woodroffe and Morrison (2001:256) argued that due to the small radiocarbon age differences between the various reef sediment constituents (c.250-350 years), it is likely that constituent grains, particularly foraminifera, are rapidly transported and deposited soon after death in reef island contexts.

Woodroffe et al. (2007) examined the depositional chronology of Warraber Island, a small sand cay in Torres Strait, based on component-specific AMS dating of sand grains, including coral, molluscs and foraminifera. A set of 32 'pristine' single grain samples were selected for dating to reduce the potential age bias produced by post-depositional reworking (Woodroffe et al. 2007). AMS results indicated that different components yielded substantially different ages with individual foraminifera tests, despite their pristine condition, returning the oldest dates from the island (4510-6639 cal BP compared to the determined time span of island progradation in the last 3000 years). Woodroffe et al. (2007:4) hypothesised that the foraminifera samples collected from the reef flat around Warraber Island were relict, speculating that they had originated from conditions associated with the mid-Holocene fossil reef and endured intermittent entrainment and re-deposition throughout the mid-to-late Holocene.

In a similar study, Dawson et al. (2014) investigated sediment production and reef-island accretion on a sand cay on Raine Island, northern Great Barrier Reef, using an extensive collection of single-grain AMS radiocarbon age determinations. A total of 100 individual large benthic foraminifera between 500µm-2mm were assigned to one of three taphonomic grades: pristine ('P'), moderately abraded ('M'), and severely abraded ('S') (Dawson et al. 2014). 'P' samples represented the initial stages of test degradation prior to fragmentation and loss of spines, while 'severely abraded' samples represented the end product of abrasion (Dawson et al. 2014). Specimens of grade 'P', 'M' and 'S' collected from nine reef flat transects were selected for AMS radiocarbon dating, along with additional grade 'P' and 'S' specimens from contemporary beach settings.

Results demonstrated that preservation (i.e. taphonomic grade) was generally related to age, implying a short time between production, mortality and deposition, typically of <10 years (Dawson et al. 2014). However, the age of severely abraded tests collected from the contemporary beach samples was found to be similar to the oldest pristine tests sampled from the reef flat. The authors suggest that the central coral zone might be a sediment sink for foraminifera which are subsequently transported to the beach zone and/or remobilised in beach sediments. In keeping with the results reported by Woodroffe et al. (2007), this implies long-term storage of foraminifera under excellent preservation conditions in certain reef flat contexts.

Elsewhere, studies have demonstrated that foraminifera can persist for thousands of years linked to favourable alkaline reservoir environments associated with high shell content (Aller 1982; Kidwell 1989; Kotler et al. 1992). As Martin et al. (1995) point out, foraminiferal preservation is likely to vary with depositional setting, meaning that the findings of Dawson et al. (2014) may be specific to Raine Island or detached reefs on the northern Great Barrier Reef. These results suggest that while there might be a general

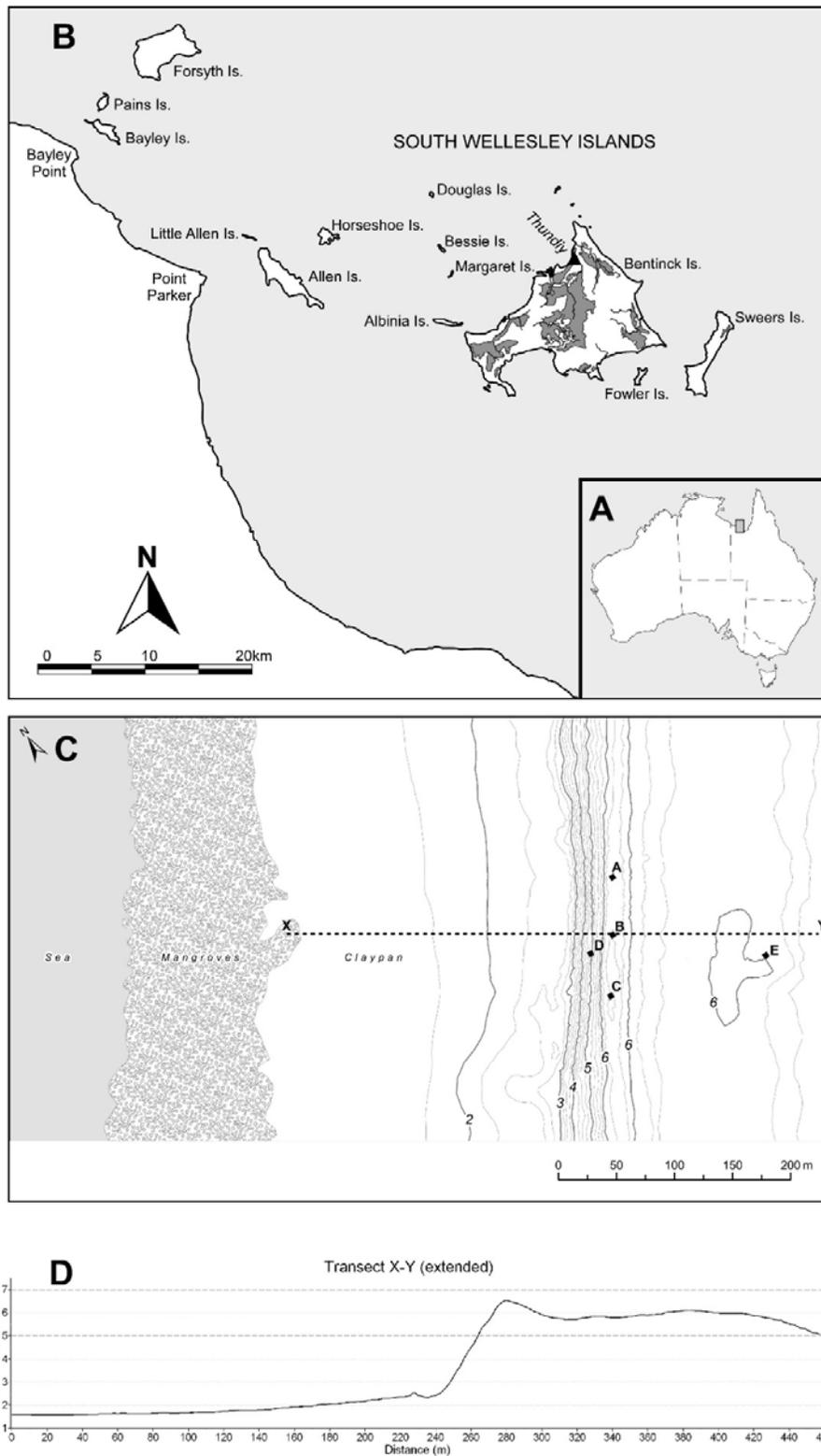
relationship between taphonomic condition and age, individual foraminifera follow unique sedimentary pathways requiring further investigation.

These studies highlight the need to identify differential preservation of foraminifera in specific environmental settings to reduce age biases. Unless robust chronologies and depositional models can be established these issues potentially undermine the validity of using foraminifera as tools for palaeoenvironmental reconstruction. AMS dating of foraminifera samples coupled with taphonomic assessment in an archaeological context is needed in order to assess the potential of foraminifera as accurate chronological and palaeoenvironmental indicators in archaeological deposits.

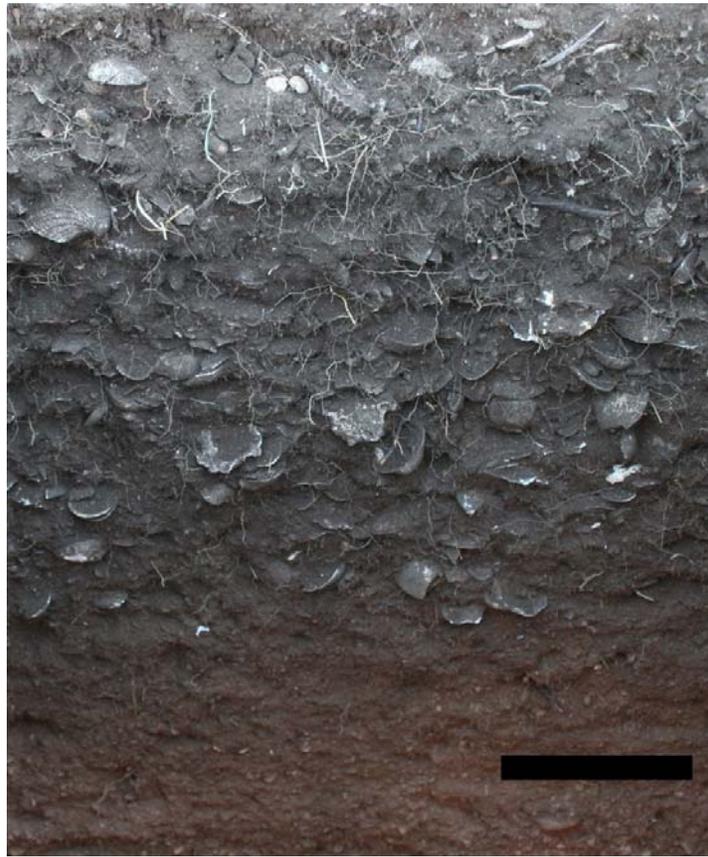
### **3. Materials and Methods**

#### **3.1 Case Study: Thundi**

Samples for this study were recovered from the archaeological shell matrix site of Thundi, located on the northern coastline of Bentinck Island in the southern Gulf of Carpentaria (Figure 1). Archaeological deposits at Thundi extend over an area c.4km long (SE-NE) and up to 150m wide (NW-SE), with dense cultural shell deposits overlying a natural shelly-beach ridge, which in turn overlies partially consolidated beachrock. The surface of the ridge is elevated 6.5m above the Australian Height Datum (AHD), with an adjacent wide flat supra-tidal mudflat (c.160m-wide) and broad, thick coastal mangrove fringe (c.120m-wide) separating the contemporary ridge from the open ocean. Sediment supply to the site derives from both natural (e.g. storm surge, wind) and cultural (e.g. disposal of food waste) actions. Three 50cm x 50cm test pits (Squares A, B and C) were excavated at 50m intervals along the top of the ridge in the approximate centre of the site with ancillary Squares D and E excavated to investigate geophysical features in a related study. Square B, the focus of this analysis, was excavated to a depth of c.60cm in 20 individual excavation units (XUs) averaging 3.2cm in thickness. The stratigraphic profile of Square B is characterised by a dense layer of shell c.40cm deep, overlying c.20cm of natural sandy beach ridge material at the base of the deposit (Figure 2). Stratigraphic profiles and ages available for Squares A and C demonstrate a similar gross chronostratigraphic structure (Table 1).



**Figure 1. (A-B)** The South Wellesley Islands, southern Gulf of Carpentaria, Australia, showing the location of Thundi on the north coast of Bentinck Island. **(C)** Topographic map of the central area of Thundi showing the location of excavation squares A-E. **(D)** Cross-section X-Y (as shown on C). Elevations relative to Australian Height Datum (AHD).



**Figure 2. Northern section of Thundiy, Square B (Photograph: Sean Ulm, 2010). Scale bar=10cm.**

**Table 1. Radiocarbon ages on marine shell and foraminifera for Thundi, Squares A-D. Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey 2009) and the Marine13 calibration dataset (Reimer et al. 2013), with a  $\Delta R$  of  $-49 \pm 102$  (Ulm 2010). All calibrated ages are reported at the 95.4% probability range. All foraminifera dated are of taphonomic grade M4 (see Table 2). All foraminifera samples are *Elphidium* sp. Shaded laboratory number cells indicate dates on natural deposits. \* = Date may extend out of range (i.e. post-AD 1950). & = Measured on CO<sub>2</sub> collected during preparation for <sup>14</sup>C dating. ^ = Measured on same graphite target as AMS using EA-IRMS. This value is similar to those measured on sample CO<sub>2</sub> because graphitisation efficiency is ~100% (i.e. no fractionation during graphitisation). # =  $\delta^{13}\text{C}$  value is assumed based on the mean of other measured *Marcia hiantina* samples. \*\* = Assumed  $\delta^{13}\text{C}$  value as measured value is not available due to limited sample size. \*\*\* = Measured on accelerator.**

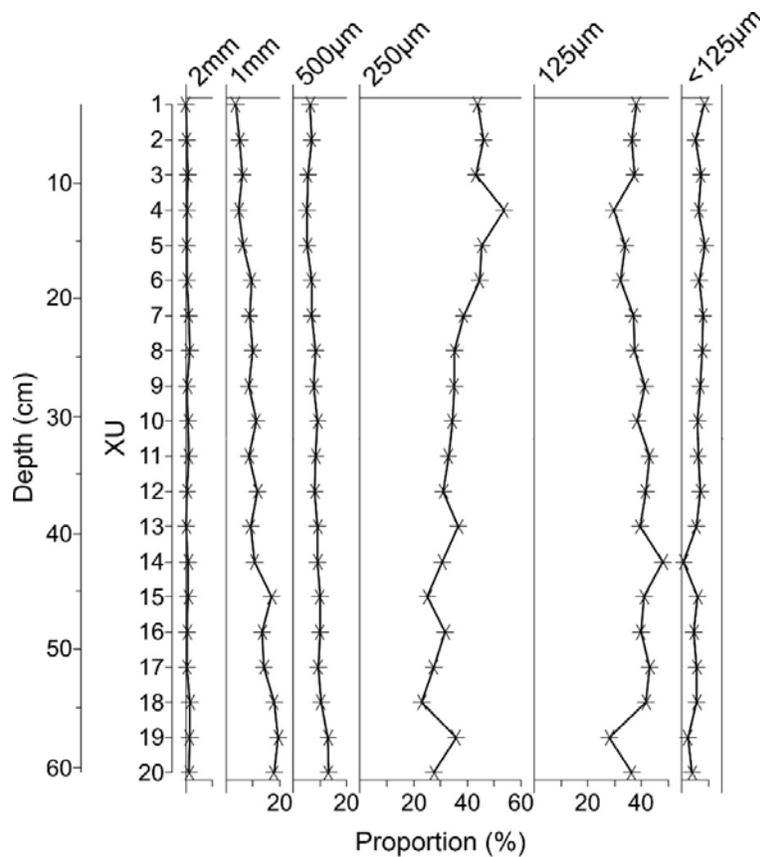
Square	XU	Depth (cm)	Sample Type	Sample (No. of Foraminifera)	Lab. No.	Method	$\delta^{13}\text{C}$ (‰)	CRA (BP)	Calibrated Age BP (95.4%)	Calibrated Age BP Median
A	1	0-2.7	Marine Shell	<i>Anadara granosa</i>	Wk-32135	Conventional	-1.6±0.2&	428±36	0*-301	132
A	1	0-2.7	Marine Shell	<i>Marcia hiantina</i>	OZP-186	AMS	-2.7±0.1^	430±35	0*-302	133
A	6	14.5-18.0	Marine Shell	<i>Anadara granosa</i>	Wk-32136	Conventional	-1.8±0.2&	611±34	0*-490	298
B	1	0-2.5	Marine Shell	<i>Marcia hiantina</i>	OZP-197	AMS	-3.3±0.1^	370±30	0*-258	104
B	4	9.34-12.34	Foraminifera	<i>Elphidium</i> sp. (n=6)	Wk-39331	AMS	***	5375±46	5568-6065	5795
B	6	15.4-18.6	Marine Shell	<i>Marcia hiantina</i>	Wk-34772	AMS	0±0.2&	851±25	309-661	510
B	9	24.5-27.5	Foraminifera	<i>Elphidium</i> sp. (n=4)	Wk-39332	AMS	***	5284±46	5461-5933	5706
B	11	30.3-33.4	Marine Shell	<i>Anadara granosa</i>	Wk-28560	AMS	-1.6±0.2&	868±30	313-674	525
B	13	36.7-39.4	Marine Shell	<i>Marcia hiantina</i>	Wk-37498	AMS	-2±0.2&	1192±22	611-1006	793
B	13	36.7-39.4	Foraminifera	<i>Elphidium</i> sp. (n=2)	OZQ-662	AMS	0**	6165±50	6394-6931	6659
B	13	36.7-39.4	Foraminifera	<i>Elphidium</i> sp. (n=2)	OZQ-538	AMS	0**	6460±80	6700-7290	7009

B	20	57.5-60.4	Marine Shell	<i>Marcia hiantina</i>	Wk-36175	AMS	1±0.2&	4716±28	4795-5305	5039
B	20	57.5-60.4	Foraminifera	<i>Elphidium</i> sp. (n=4)	OZQ-663	AMS	-1.3^	5615±40	5827-6301	6067
B	20	57.5-60.4	Foraminifera	<i>Elphidium</i> sp. (n=4)	OZQ-539	AMS	0**	5890±60	6105-6639	6362
C	1	0-2.7	Marine Shell	<i>Marcia hiantina</i>	OZP-187	AMS	-1.6±0#	435±30	0*-304	135
C	11	31.4	Marine Shell	<i>Anadara granosa</i>	Wk-28561	AMS	-1.3±0.2&	1139±30	549-934	747
C	15	41.7-44.7	Marine Shell	<i>Marcia hiantina</i>	Wk-36176	AMS	0.3±0.2&	4484±29	4421-4985	4717
C	20	56.5-59.6	Marine Shell	<i>Gafrarium tumidum</i>	Wk-36177	AMS	2±0.2&	4682±28	4724-5292	4997
D	13	35	Marine Shell	<i>Gafrarium tumidum</i>	Wk-40103	AMS	***	4942±21	5036-5571	5334

### 3.2 Analytical Procedures

Sediment samples (~10g) from each of the 20 excavation units were selected by quartering the bulk <3mm sediment samples (after Pope and Ward 1998). Each sample was separated into fractions using nested Endecotts sieves (2mm, 1mm, 500 $\mu$ m, 250 $\mu$ m, 125 $\mu$ m and the base plate fraction at <125 $\mu$ m) (Haynes 1981). The <250 $\mu$ m sieve fractions were not analysed further owing to size limitations (i.e. foraminifera were too small for AMS radiocarbon dating and to work with effectively). The removal of the <250 $\mu$ m sieve fractions reduced the original 10g samples to ~6g (i.e. a reduction of 42%) (Figure 3).

Following the methods outlined in Rosendahl et al. (2007), each sieve fraction was transferred to a glass petrie dish and systematically examined in optical transects using a Wild M3 Stereo Microscope. Individual foraminifera were transferred into a picking tray (Haynes 1981), before storage in glass vials. Test morphology formed the basis of species classification aided by reference texts (Albani 1968, 1979; Cushman 1948; Murray 1971, 1991) and the World Online Foraminifera Database (Hayward et al. 2013). Each taxon of foraminifera was quantified by establishing minimum number of individuals (MNI). MNIs of each species were obtained by counting the umbilical phenotype. To enable comparative analysis, densities are reported as the number of foraminifera per 100g of sediment (after Rosendahl et al. 2007).

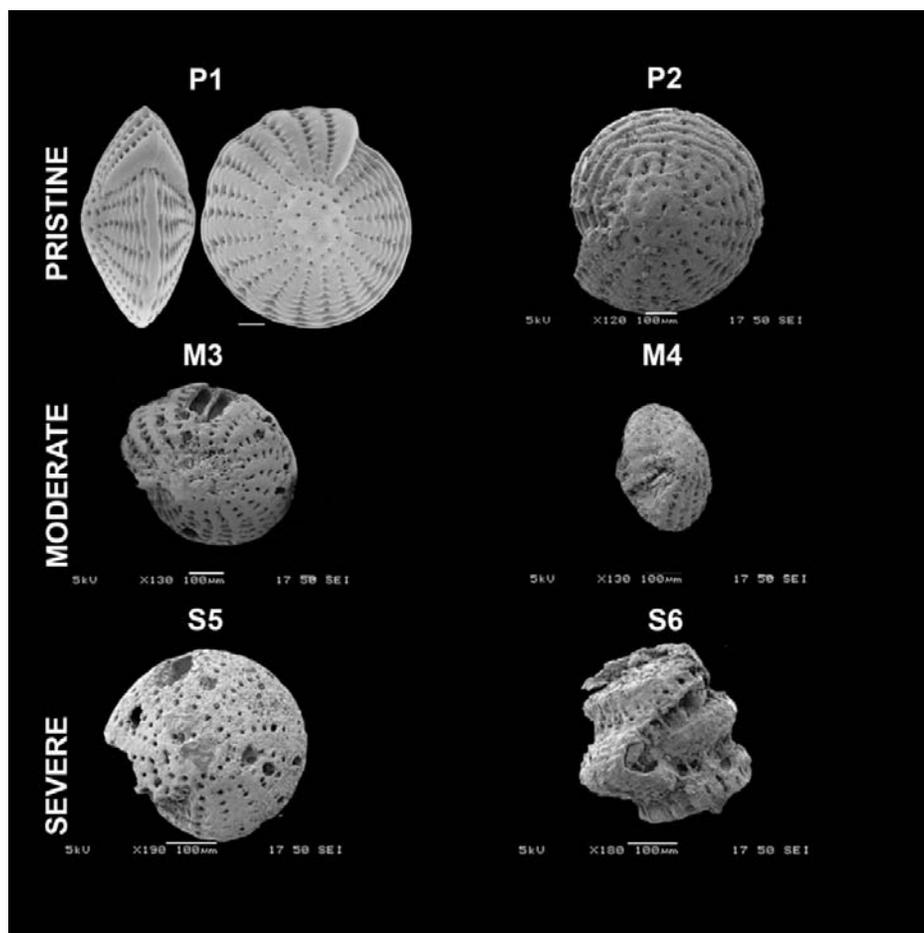


**Figure 3. Proportion (%) of sediment retained in each sieve fraction and excavation unit (XU), Thundi, Square B.**

Expanding Dawson et al.'s (2014) 3-class classification index, individual foraminifera tests were systematically categorised into one of six taphonomic grades, ranging from pristine to severe, based on defined structural and surficial taphonomic indicators that are characteristic of foraminifera assemblages in archaeological contexts (Table 2). In this index, 'pristine' (P1) is an ideal foraminifera equivalent to a live-collected specimen that has not undergone post-mortem transport (Figure 4).

**Table 2. Attribute matrix used to assess the taphonomic condition of individual foraminifera.**

Taphonomic Indicator	Pristine (P1)	Pristine (P2)	Moderate (M3)	Moderate (M4)	Severe (S5)	Severe (S6)
Calcification	None	Slight	Moderate	Moderate	Heavy	Heavy
Fragmentation	None	None	Slight	Moderate	Moderate	Heavy
Abrasion	None	None	Slight	Moderate	Moderate	Heavy



**Figure 4. Examples of pristine (P1-P2), moderately abraded (M3-M4) and severely abraded (S5-S6) foraminifera (all examples are *Elphidium* sp.). P1 from <http://www.marinespecies.org/foraminifera/aphia.php?p=taxdetails&id=478589> and reproduced with permission. P2-S6 from collection of the authors.**

### 3.3 AMS Radiocarbon Age Determinations

Twenty-two samples of foraminifera (6 from XU4, 4 from XU9, 4 from XU13 and 8 from XU20) from Square B were selected for AMS dating. All samples were *Elphidium* sp. as they were the dominant taxa, represented throughout the deposit and dating a single taxon controlled for inter-taxa differences in susceptibility to degradation. The 250µm and 500µm samples were found to be too small to be dated individually, as specimens did not contain enough mass for producing precise results. It is possible to combine small samples to yield enough carbon mass, however, only the 500µm sample size was considered practicable for this solution, as a large number of 250µm samples would be required to produce the necessary amount of carbon which would reduce the level of chronological control. 1mm samples were found to be large enough to date individually. However, <1% (n=2) of foraminifera retrieved from Thundi were retained in the 1mm sieve fraction. As a result, we combined samples of 500µm foraminifera to minimise the mixing of a large number of samples of potentially different ages. Although the use of a small number of foraminifera per sample for dating rather than individual specimens is not ideal, their <sup>14</sup>C ages likely represent similar individual ages rather than a mixture of different ages (see Section 4.2 for discussion). Four AMS ages were undertaken at the ANTARES AMS facility at ANSTO (Fink et al. 2004; Hua et al. 2001) and two samples were measured at the Waikato Radiocarbon Laboratory. Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey 2009) and the Marine13 dataset (Reimer et al. 2013), with a  $\Delta R$  of  $-49 \pm 102$  <sup>14</sup>C years for marine samples from the Gulf of Carpentaria (Ulm 2010). All calibrated ages are reported at the 95.4% probability range. Since the Gulf of Carpentaria has a maximum depth of <70m (Torgersen et al. 1983), marine organisms are assumed to have <sup>14</sup>C activities close to coeval surface waters, and  $\delta^{13}\text{C}$  measurements of benthic foraminifera show that >95% of carbon appears to derive from Dissolved Inorganic Carbon (DIC) (Broecker et al. 1984:339).

## 4. Results

### 4.1 Foraminifera Assemblage and Taphonomic Grading

A total of 298 individual benthic foraminifera were identified, ranging from 15.8 MNI/100g in XU4 to 879 MNI/100g in XU20 (Table 3). The sediment samples were anticipated to have highly varied quantities of foraminifera due to the obvious presence of both natural and cultural shell material at Thundi. MNI data show a clear increase in foraminiferal densities towards the base of the deposit, representing the transition between the overlying cultural deposits and the beach ridge formation below. The cultural units in the top third of the deposit (XU1-7) exhibited an average foraminifera density of 77 MNI /100g, while the natural units in the bottom third of the deposit (XU14-20) had an average density of 553 MNI/100g, while the intervening deposit (XU8-13) was 166 MNI/100g (Table 3).

Of the 298 foraminifera, 262 (88%) were retrieved from the 250µm sieve fraction. The 2mm sieve fraction did not contain any foraminifera; the 1mm sieve fraction exhibited only 2 individuals which represents <1% of the total foraminifera retrieved from Thundi; and the 500µm sieve fraction exhibited 34 individuals (11%). These findings indicate that the recovery rate of larger foraminifera (500µm, 1mm and 2mm) in archaeological sediments is rare, with implications for carbon yields for AMS dating (see also Rosendahl et al. 2007, 2014).

The Thundi foraminifera assemblage is co-dominated by *Elphidium* sp. and *Ammonia convexa*. Foraminifera were identified to species level, however, due to limitations in identification arising from weathering and calcification, some specimens were classified to genus level only (e.g. *Elphidium* sp.). Several species of *Elphidium* sp. share very similar morphological attributes (e.g. *E. craticulatum* and *E. hispidulum*) reducing confidence in taxa identification beyond the genus level. If there was any ambiguity in identifying individual foraminifera they were classified as ‘unidentified.’

## 4.2 Stratigraphy and Geochronology

The chrono-stratigraphic framework of Thundi is characterised by a dense layer of cultural shell which overlies natural beach ridge material and basal beachrock ridge. Thirteen radiocarbon ages on suspension-feeding marine bivalves (*Anadara granosa*, *Marcia hiantina*, *Gafrarium tumidum*) from Squares A-D show that cultural deposits date to between 104 and 793 cal BP with a sharp chronostratigraphic disjunction to the lower beach ridge dating between 4717 and 5039 cal BP. The sandy beach ridge deposits overlie beachrock dated on a *G. tumidum* concreted into its surface to 5334 cal BP (Table 1, Figure 5). The beachrock comprises nearshore sediments indurated by precipitation and cementation of calcium carbonate during the most recent postglacial marine transgression as sea-level rose above present mean sea-level level (PMSL) to c.2 to 2.5m above PMSL by 7000 cal BP followed a sea-level highstand until c.2000 years ago (Reeves et al. 2008; Sloss et al. 2012; Lewis et al. 2013). These ages indicate a >3000 year hiatus between the formation of the natural shelly-beach ridge and subsequent initiation of cultural occupation c.800 cal BP (Figure 5). Between the natural and cultural deposit there is a transitional zone with some mixing of cultural material with the underlying natural deposit. The natural layer underlying the cultural layer is a sandy beach ridge comprising fine-to-medium-grained siliciclastic sand, with common shell fragments and grading down section into the consolidated beachrock (Figure 2).

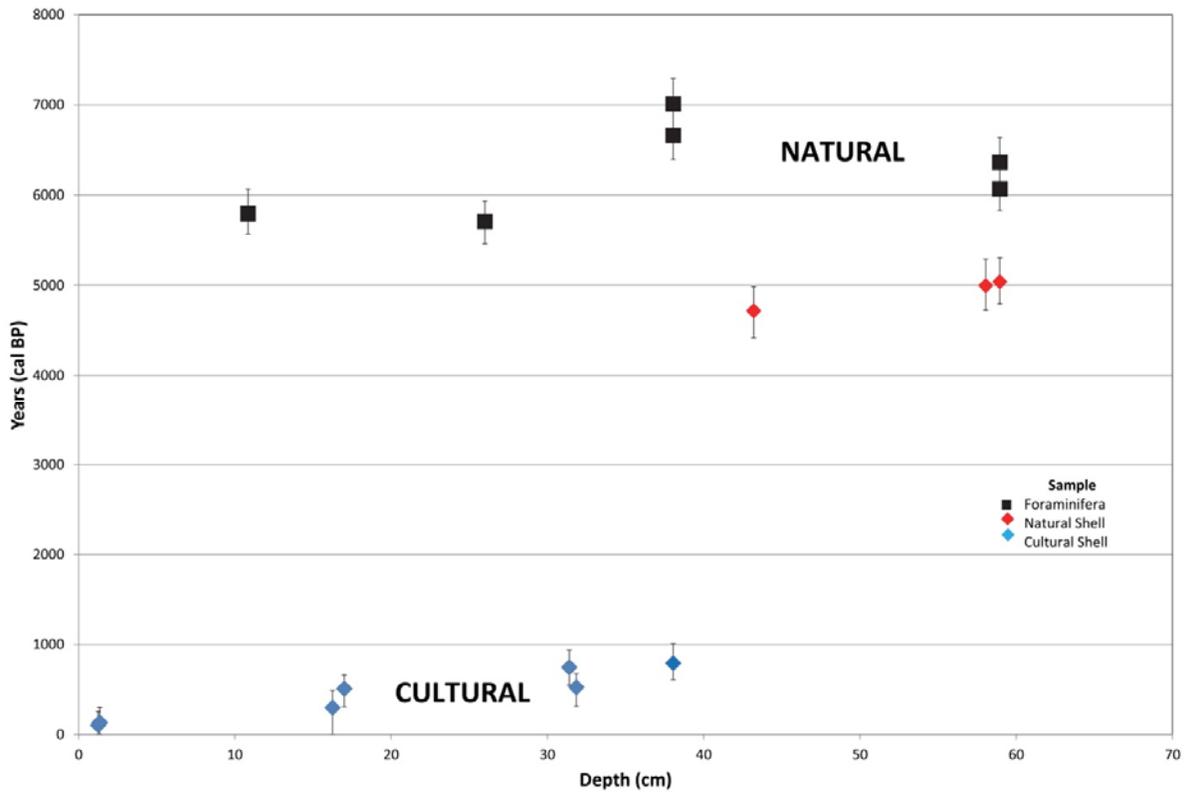
Six AMS radiocarbon ages of 22 individual foraminifera (all *Elphidium* sp.) sampled from XUs 4, 9, 13 and 20 returned median calibrated ages between 5706 to 7009 cal BP (Table 1). All of the selected foraminifera were in moderate (M4) condition. Although small numbers of individual foraminifera (n=2-6) were combined to yield sufficient carbon mass, the close agreement in age between duplicate samples for both XU13 and XU20 indicates that individual foraminifera in these two sets of samples are likely to have similar ages. In other words, these <sup>14</sup>C ages represent similar individual ages rather than a mixture of different ages. The AMS results from foraminifera were compared with conventional radiocarbon ages of marine bivalves from the same deposit (Table 1, Figure 5), showing that the samples of foraminifera are more than 1000-2000 cal years older than samples of bivalve shell dated from the same context.

*Elphidium* sp. represents 43% (n=128) of the total assemblage and *A. convexa* 20.8% (n=62) with 36.2% (n=108) unidentified (Table 3). Both species are characteristic of shallow, intertidal, marginal marine environments (Sen Gupta 1999). The foraminiferal assemblage reflects the local environment surrounding Thundi, which is characterised by coastal tidal/intertidal zones and estuarine systems, with dynamic substrates situated in a tropical marginal marine zonation.

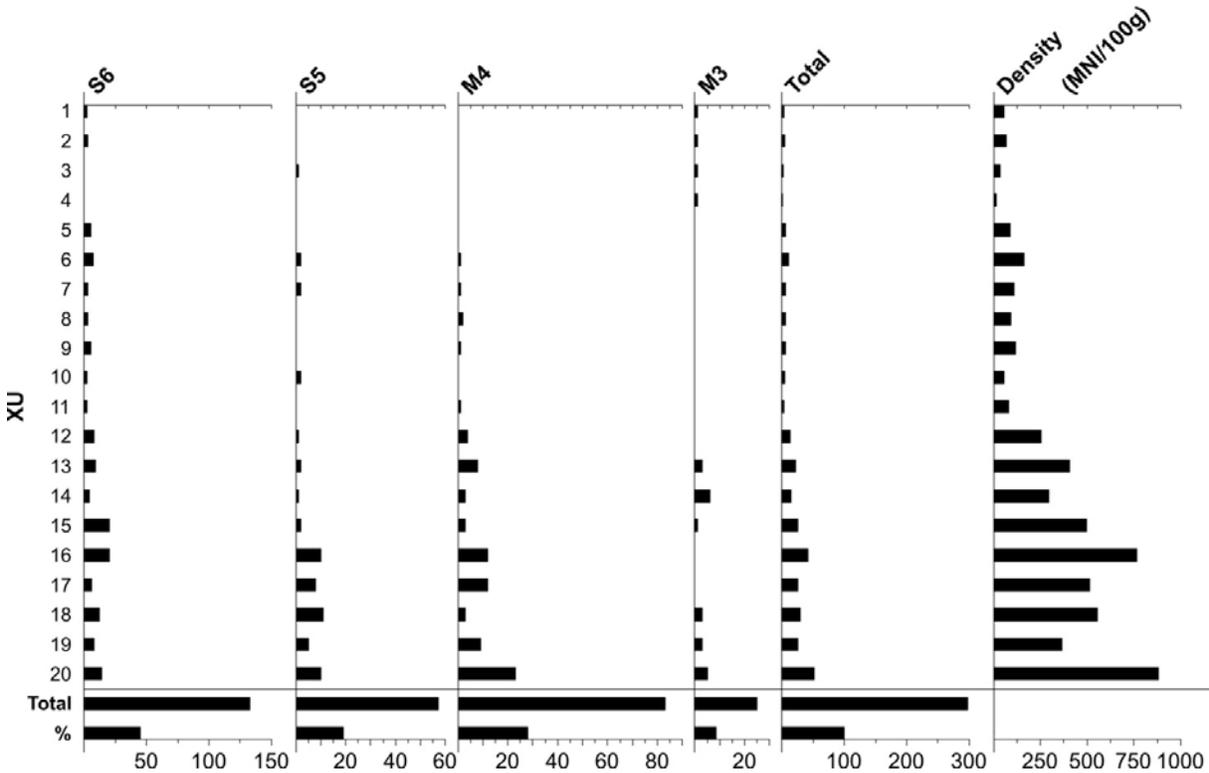
The majority of foraminifera recovered from Thundi were in a severe condition, with 45% classified as S6 and 19% in S5 (Figure 6). The rest of the assemblage was classified in the moderate categories, with 28% of individuals categorised as M4 and 8% in the M3 category. No individuals were recovered in pristine (P1 and P2) condition. Results indicate a strong representation of tests in severely abraded condition throughout the deposit, with small numbers of tests of moderate condition.

**Table 3. Foraminifera assemblage attributes, Thundi, Square B.**

XU	Depth (cm)	Sediment Analysed (g)	MNI (#)	Density (MNI/100g)	<i>Ammonia beccarii</i>	<i>Elphidium</i> sp.	Unidentified
1	2.5	5.30	3	56.51	1	2	0
2	5.4	5.81	4	68.82	0	1	3
3	9.3	5.52	2	36.22	1	0	1
4	12.3	6.34	1	15.75	1	0	0
5	15.4	5.70	5	87.59	0	2	3
6	18.6	6.10	10	163.7	2	4	4
7	21.4	5.50	6	108.95	0	4	2
8	24.5	5.45	5	91.65	0	3	2
9	27.5	5.13	6	116.92	0	5	1
10	30.3	5.49	3	54.57	0	1	2
11	33.3	5.04	4	79.35	0	3	1
12	36.7	5.16	13	251.6	0	9	4
13	39.4	5.44	22	404.35	1	15	6
14	42.4	4.77	14	293.38	0	9	5
15	45.5	5.25	26	495.02	1	5	20
16	48.6	5.47	42	767.29	6	16	20
17	51.6	5.06	26	513.51	10	9	7
18	54.5	5.21	29	555.61	13	8	8
19	57.5	6.85	25	364.87	10	11	4
20	60.4	5.91	52	879.01	16	21	15
TOTAL		110.5	298	-	62	128	108



**Figure 5. Calibrated age-depth plot of all radiocarbon dates available for Thundi, Squares A-D. See Table 1 for details. Error bars are 2-sigma (95.4% probability). Note that four individual determinations from the surface of the site cluster around 100 cal BP. A single determination listed in Table 1 from Square D (Wk-40103) is not shown as it is from the side of the ridge with a different age-depth relationship to the other ages shown.**



**Figure 6. Taphonomic grades represented in the foraminifera assemblage, Thundi, Square B. See Table 2-3 for definitions.**

## 5. Discussion

### 5.1 Depositional and Taphonomic Influences on Foraminifera Preservation

An elaboration of Dawson et al.'s (2014) foraminifera taphonomic classification scale proved effective for grading the condition of individual foraminifera in archaeological sediments. Results of the taphonomic analysis indicate that the majority of tests are in a severely degraded condition with the remainder recovered in moderate condition. The presence of both moderate and severe specimens from the surface to the base of the deposit (Figure 6) does not conform to expectations of a standard decay profile. Despite the overall density of foraminifera increasing towards the base of the deposit, the ratio of severe:moderate tests decreases from the top (XU1-7=3.57:1) to the base (XU14-20=2.21:1) of the deposit. No tests were categorised in pristine condition due to a significant amount of weathering and calcification evident in tests recovered throughout the deposit. The condition of individual tests present at Thundi reflects the numerous site formation and post-depositional processes that influence coastal archaeological deposits. Moreover, the lack of pristine foraminifera present at the site demonstrates the complex taphonomic pathways of foraminifera in archaeological and natural deposits, suggesting that specimens have been subjected to degradation during transport and reworking, or have been significantly altered by post-depositional taphonomic processes. The varied taphonomic condition of foraminifera tests present throughout the Thundi deposit likely reflect stages of degradation that have occurred during foraminifera transport and residence time in sediment sinks, prior to remobilisation and deposition. This highlights the importance of considering the unique taphonomic pathways that act on each individual foraminifera prior to and after deposition.

AMS dating results show that sampled foraminifera are at least 1000-2000 cal years older than samples of marine bivalve shell dated from the same contexts. All of the marine bivalve shell ages are in consistent age-depth order and the determinations are all on suspension-feeding marine bivalves (*A. granosa*, *M. hiantina*, *G. tumidum*) that have been shown to be reliable genus for dating in well-flushed environments and in the absence of limestone (Petchey et al. 2013; Southon et al. 2002). It is unlikely that densely packed shell valves with large surface areas such as that contained in the lens have moved far in the deposit (see Hughes and Lampert 1977) resulting in an inaccurate chronology. Consequently, the age discrepancy of the dated foraminifera samples raises a number of issues about the validity of utilising foraminifera for AMS dating and palaeoenvironmental reconstruction in highly dynamic depositional settings. Issues of differential preservation inherent in foraminifera test morphology, time averaging and post-depositional reworking are proposed as possible explanations for the reservoir times evident in the foraminifera ages from the Thundi deposit.

Some species of foraminifera preserve better than others owing to their varied morphological characteristics and mineralogy, which can cause a taphonomic bias even in recent sedimentary records (Broecker et al. 1984; Sen Gupta 1999:4). Studies investigating the taphonomy of foraminifera tests in intertidal environments show that the surface mixed layer of sediment can act as a low-pass filter that contributes to time-averaging, facilitating the preservation of foraminifera tests in a calcium-carbonate rich, sub-surface taphofacies (Martin et al. 1995; Sen Gupta 1999). Martin et al. (1995) found that some contemporary samples of foraminifera collected from the intertidal zone in Choya Bay, Mexico, were surprisingly old (c.2000 years based on AMS dates), despite evidence for intensive dissolution among contemporary foraminifera present in the area. Older tests were recovered in pristine condition suggesting that these tests were resistant to dissolution and extremely well-preserved for an extensive period of time. Martin et al. (1995) hypothesised that some foraminifera tests survived dissolution due to transportation by conveyor belt deposit feeders into a shell-rich sub-surface sediment layer through downward bioturbation, preserving the tests until subsequent reworking by upward bioturbation or storm activity. As a result, the study concluded that the taphonomic grade of tests was not a reliable indicator of test age and that the dynamics of individual test preservation must be considered in assessing time-averaging of microfossil assemblages (Martin et al. 1995).

Similarly, foraminifera samples recovered from Thundi may have complex taphonomic histories that reflect the residence time of the dated specimens in the sedimentary system as a result of differential preservation among foraminifera in the intertidal zone. Production and deposition of foraminifera would have changed dramatically across the Holocene with sea-level rise peaking around Bentinck Island between 2 and 2.5 m above PMSL by 7000 cal BP followed a sea-level highstand until c.2000 years ago, resulting in the formation of beach rock and aeolinite, and the initiation of beach ridge, mudflats and mangrove swamp environments (Sloss et al. 2012).

Preliminary radiocarbon ages from estuarine bivalves preserved below the modern claypan in transgressive and mangrove deposits east-southeast of Thundi provide age determinations of 4108 to 6090 cal BP corresponding with the end of the most recent post-glacial marine transgression and Holocene sea-level highstand (Sloss et al. 2012). These mid-Holocene transgressive and mangrove highstand deposits provide a reservoir locale for the local storage of foraminifera before intermittent remobilisation and re-deposition over the mid-to-late Holocene (see also Woodroffe et al. 2007; Woodroffe and Morrison 2001; Dawson et al. 2014).

The moderate condition of the dated foraminifera samples >6000 cal BP are a testament to the ability of intertidal species such as *Elphidium* sp. to withstand dissolution and to be well-preserved in some environmental and depositional contexts, even in tropical monsoonal environments. In this context, foraminifera tests are likely to remain in the substrate immediately north of the Thundi site, being moved through the substrate by bioturbation (e.g. conveyor belt feeders) and entering the site during periodic storm surges and/or erosion/deposition events.

## 5.2 Archaeological Implications

Foraminiferal analysis was successful in differentiating between the natural and cultural stratigraphic components in the Thundi sequence. Foraminiferal densities showed a clear increase towards the base of the excavated deposit, denoting the transition between the overlying cultural deposits and the natural beach ridge below. The mean densities of the cultural deposit (77 MNI/100g) lay outside the previously established parameters set for cultural and natural deposits of <50 MNI/100g and >1000 MNI/100g respectively (Rosendahl et al. 2007). However, they fall within the parameters reported for low energy wave deposition of sediments observed on nearby Mornington Island (Rosendahl et al. 2014). Regional variations in densities of foraminifera represented in nearshore-influenced terrestrial deposits should be expected given significant differences in production rates, amplitudes and periodicities in the local environment, coupled with differences in wind, wave and storm transport pathways and the depositional setting.

Most (88%) foraminifera were recovered in the 250 $\mu$ m sieve fraction. In contrast, only 11.4% of foraminifera were retained in the 500 $\mu$ m fraction, and <1% of individuals are represented in the 1mm sieve fraction. The skewing of foraminifera sizes in archaeological deposits towards these smaller size classes (also documented by Rosendahl et al. 2007) has implications for attaining the minimum carbon requirement for precise AMS radiocarbon dating, which, due to the rarity of individuals retained in the 500 $\mu$ m, 1mm and 2mm sieve fractions, may require an increase in sediment samples of this size range to obtain the rarer size classes represented in archaeological deposits. However, caution must be exercised as selecting larger foraminifera for dating may not provide a representative sample of foraminifera size ranges in the deposit which will be skewed towards smaller sieve fractions. Ideally, we recommend that single foraminifera be dated in future studies from dominant size classes (i.e. 250 $\mu$ m in this case), requiring further consideration of small sample AMS analysis.

## 6. Conclusions

AMS dating of foraminifera reveals a weak relationship between preservation status and age in the Thundi deposit. Foraminifera ages are inconsistent with dates obtained from bivalves suggesting foraminifera may be unreliable targets for dating marine-influenced terrestrial deposits. We suggest that foraminifera residence ages accrue from storage in shelly components of saltpans and claypans adjacent to the site, before remobilisation and redeposition, explaining both the good state of preservation and residence ages of the dated specimens. Differential preservation between numerous foraminifera species in diverse marine environments may significantly impact the age of assemblages, regardless of their taphonomic condition, as evidenced by the foraminifera reported here. Consequently, the dynamics of differential preservation inherent in various foraminifera species and environmental contexts need to be considered, irrespective of taphonomic condition, prior to sampling foraminifera for the purposes of AMS dating to ensure the most accurate results. These results suggest that caution is required in the analysis and interpretation of

foraminifera in palaeoenvironmental reconstructions in highly dynamic depositional settings, particularly for the provision of accurate age control.

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