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Early Human Occupation of a Maritime Desert, Barrow Island, North-West Australia

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Abstract

Archaeological deposits from Boodie Cave on Barrow Island, northwest Australia reveal some of the earliest evidence for Aboriginal occupation of Australia, along with demonstrating early systematic use of marine resources by modern peoples outside of Africa. Barrow Island is a large (202 km^2) limestone continental island located on the North-West Shelf of Australia, optimally located to sample past use of both the Pleistocene coastline and extensive arid coastal plains. An interdisciplinary team forming the Barrow Island Archaeology Project (BIAP) has addressed questions focusing on the antiquity of occupation of coastal deserts by hunter-gatherers; the use and distribution of marine resources from the coast to the interior; and the productivity of the marine zone with changing sea levels. Boodie Cave is the largest of 20 stratified deposits identified on Barrow Island with 20 m^3 of cultural deposits excavated between 2013 and 2015. In this first major synthesis we focus on the dating and sedimentology of Boodie Cave to establish the framework for ongoing analysis of cultural materials. We present new data on these cultural assemblages – including charcoal, faunal remains and lithics – integrated with micromorphology, sedimentary history and dating by four independent laboratories. First occupation occurs between 51.1 and 46.2 ka, overlapping with the earliest dates for occupation of Australia. Marine resources are incorporated into dietary assemblages by 42.5 ka and continue to be transported to the cave through all periods of occupation, despite fluctuating sea levels and dramatic extensions of the coastal plain. The changing quantities of marine fauna through time reflect the varying distance of the cave from the contemporaneous shoreline. The dietary breadth of both arid zone terrestrial fauna and marine species increases after the Last Glacial Maximum and significantly so by the mid-Holocene. The cave is abandoned by 6.8 ka when the island becomes increasingly distant from the mainland coast.

Keywords: North-West Shelf of Australia; colonisation; coastal deserts; maritime deserts; marine resources; island archaeology

Highlights

- New evidence for early occupation of a coastal desert in NW Australia

- Bayesian analysis places first human occupation at Boodie Cave 51.1– 46.2 ka

- Dates provide one of the earliest brackets for the colonisation of Australia

- Arid zone plains fauna are well represented in the earliest dated units

- Initially small, then expanding use of marine resources

- Early assemblages illustrate systematic exploitation of the now-drowned coastal plain

1. Introduction

The islands of the North-West Shelf of Australia provide a unique opportunity to address several inter-related questions focusing on the archaeology and palaeoenvironment of the coastal-desert interface. Here we focus on the antiquity and nature of occupation of coastal deserts; the use and distribution of marine resources across the Pleistocene coastal plain; and profile data on the relative productivity of the marine zone. Barrow Island now lies 60 km from the mainland and is optimally located on the edge of the continental shelf to sample earlier marine adaptations and occupation of the now-drowned North-West Shelf.

A three year survey program of the 202 km^2 limestone island located 30 open surface sites and 20 caves and rockshelters, of which Boodie Cave is the largest at > 3,000 m^2 (Fig. 1 and 2 and Appendix Figs. A1–A5). These sites, and others on the nearby Montebello Islands, were abandoned by 6.8 ka when rising sea levels reached their present levels. Abandonment and lack of evidence for re-incorporation by watercraft-using peoples after this date, likely reflects their significant distance off-shore and the declining returns for risk consistent with models of island human biogeography for Indo-Australian waters (Kealy et al. 2016; Manne and Veth, 2015; Veth et al., in press; Ward et al., 2014, 2015). In this study, we present evidence for occupation dating to between 51.1 ka and 46.2 ka, with direct dates on shellfish from 42.5 ka representing the oldest marine dietary remains in Australia. Equivalent-aged dietary molluscan and fish remains have been reported in other ancient limestone contexts from New Ireland, Timor-Leste and Niah Cave in Borneo (Barker, 2013; Langley et al. 2016; Leavesley and Chappell, 2004; O'Connor et al., 2011). Several sites from Cape Range located to the southwest of Barrow Island have previously returned dates in the 39–35 ka range (Morse, 1999). The increasing body of evidence for early and ongoing occupation of coastal deserts is consistent with recently obtained dates for the occupation of interior deserts and models for coastal dispersion in Australia (Bird et al., 2016; Hamm et al., 2016; O'Connell and Allen, 2012; Veth et al., in press; Ward et al., 2014; Wood et al., 2016). The early consistent use of marine resources by peoples occupying the Australian North-West Shelf throughout the terminal Pleistocene attests to the relative productivity of the coastline during lowered sea stand (Ward et al., 2015; D'Alpoim Guedes, 2016).

While it is widely acknowledged that most sites with evidence of early marine resource use have been drowned by rising sea levels, our deliberate targeting of Barrow Island has provided the earliest evidence for early coastal economies and lifeways in northern Australia (Erlandson and Braje, 2015; Veth et al., 2014; Ward et al., 2013; and see Morse 1999).
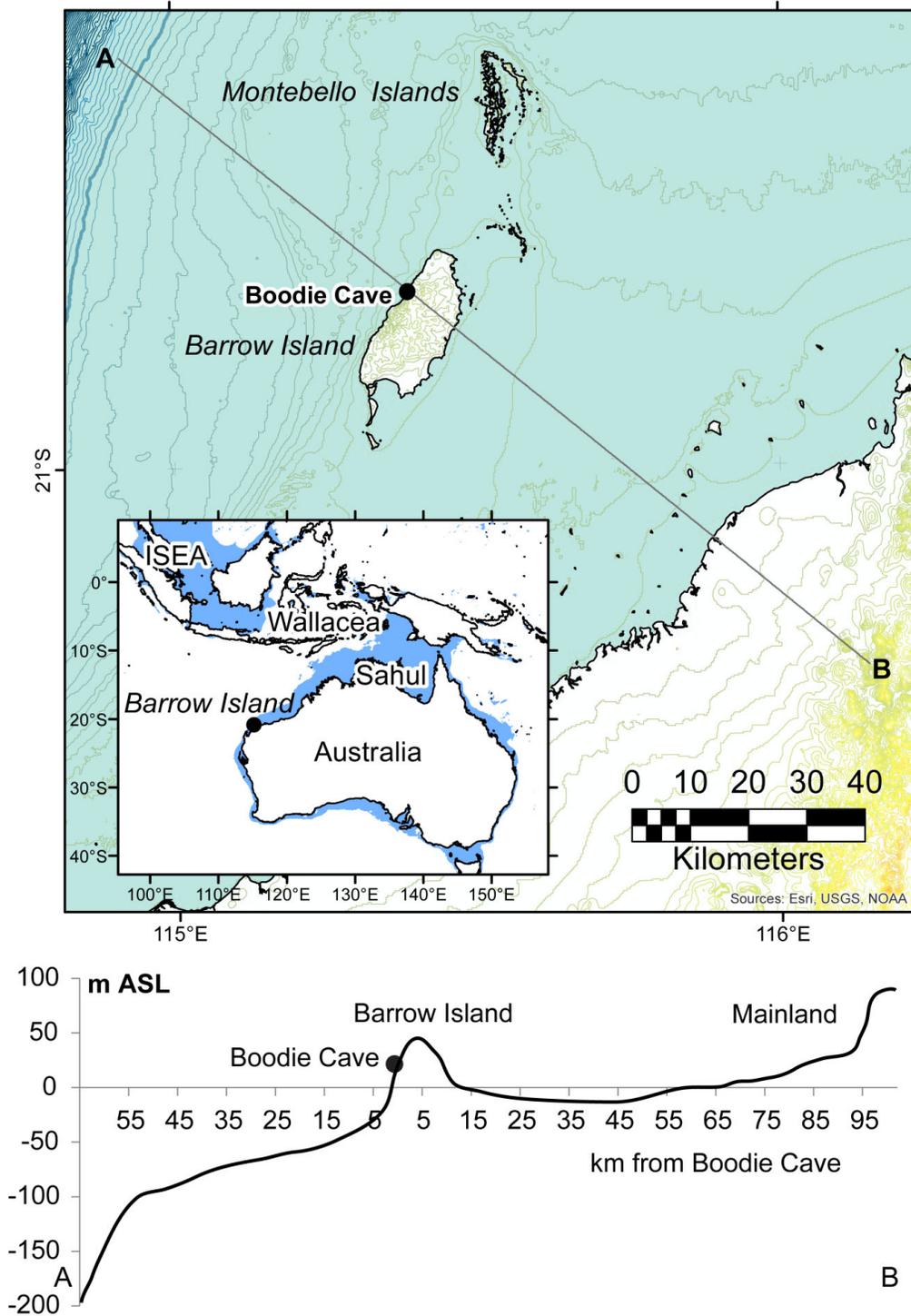
Figure 1. Location of Boodie Cave, Barrow Island, near the edge of the North-West Australian continental shelf, with transect A-B from the shelf edge to the mainland (profile, bottom panel). Bathymetry in 10 m intervals. Thick bathymetric line is -130 m, denoting the approximate position of the coast at LGM. Inset shows Sahul (Australia, New Guinea and Tasmania, and formerly emergent continental shelves as blue shading), Wallacea and Island South-East Asia (ISEA).

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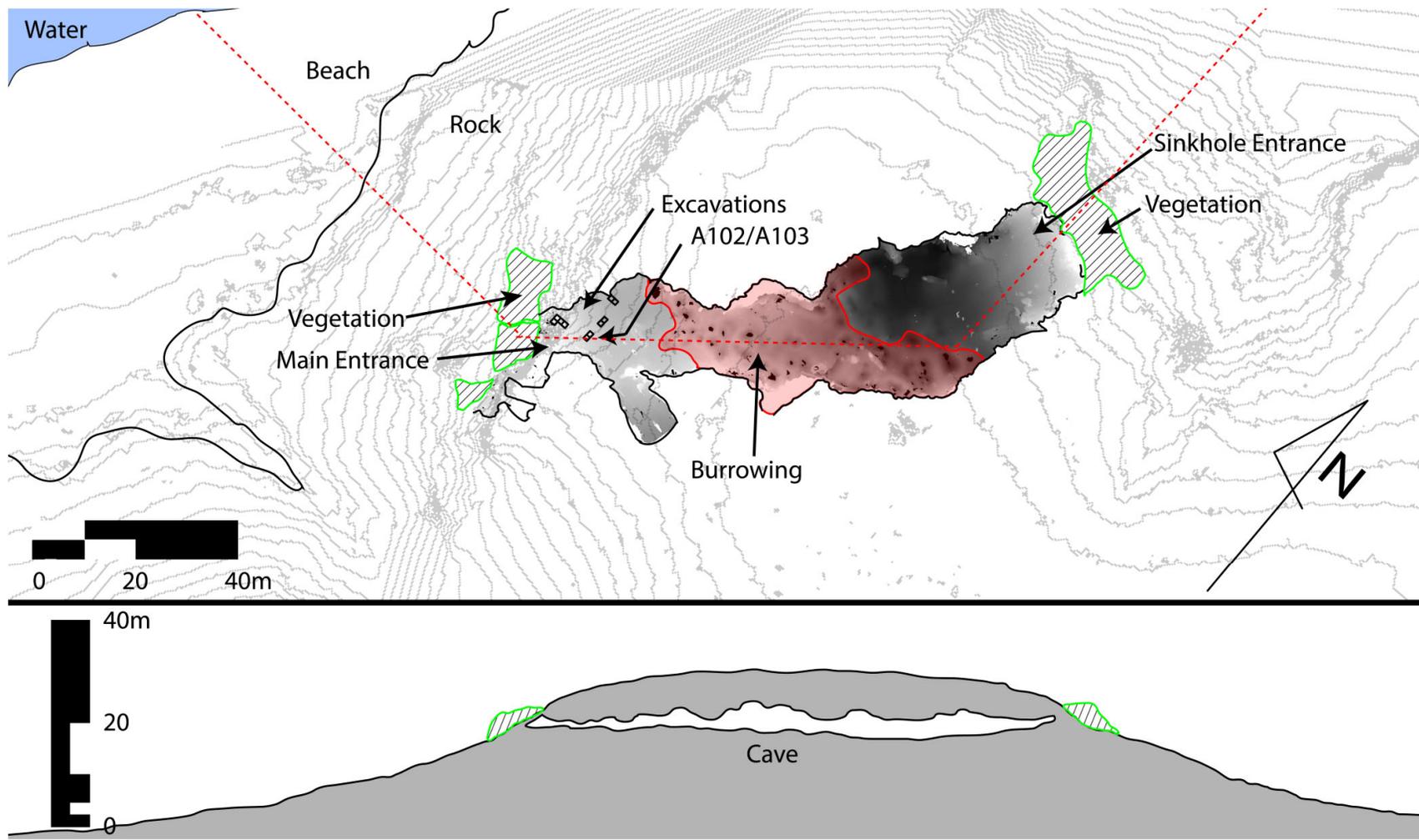
Figure 2. Plan and cross-section of Boodie Cave showing its position in relation to present shoreline and location of excavation trenches and other features. Contours are in 1 m intervals.

1.1 Regional Setting

Barrow Island is located on the North-West Shelf of Western Australia (Fig. 1) and lies within the northern Carnarvon bioregion (Kendrick and Mau, 2002; Veth et al., 2014). The island is part of the Trealla Limestone formation that covers much of the North-West Shelf providing shelters and caves with excellent preservation for archaeological deposits (Veth et al., 2007). The climate is arid with 300 mm of variable summer and winter rainfall. Details on the environmental and historical (industrial) context of Barrow Island are provided by Moro and Lagdon (2013).

Located on the northwestern coast of Barrow Island, Boodie Cave is optimally positioned near the edge of the Australian continental shelf (Fig. 1). For most periods of lower sea level this cave would have been within the foraging range of the Pleistocene coastline; the thick bathymetric line at -130 m denotes the approximate position of the coast during the Last Glacial Maximum (LGM) between 22–18 ka. This large island was connected to the mainland for the duration of the terminal Pleistocene and early Holocene, eventually becoming a super-island connected to the Montebello Islands by an isthmus. This was drowned and the islands became a far flung archipelago after c. 8 ka (Veth et al. 2007).

2. Material and Methods

2.1 Field Methods

Boodie Cave and the surrounding valley were surveyed using a Leica C10 Terrestrial Laser Scanner (Vosselman and Maas, 2010; Leica, 2011). A representative cross-section of the cultural deposits was excavated over three successive field seasons (2013–2015) by way of 10 sample squares. These provide a sample from outside the cave mouth to the interior edge of the light zone, comprising c. 20 m^3 of deposit (Fig. 2; Appendix Fig. A4). This represents a significant sample volume within the wider Australian context (Langley et al., 2011). In this paper we report on a well-preserved and well-dated record from two of the sample squares, A102 and A103.

Disturbance by burrowing bettongs (*Bettongia lesueur*) is limited to darker parts of the cave with the first 10–15 m of the cave entrance unaffected by their activities (Fig. 2) (Manne and Veth, 2015). Excavation was carried out in c. 2–3 cm excavation units within stratigraphic units, to a depth of 220 cm through archaeological deposits to a culturally sterile unit below 180 cm. Augering to 3.5 m revealed a continuing culturally sterile deposit. The locations of stratigraphic features, micromorphology columns and *in situ* finds – comprising charcoal, lithic and shell artefacts, and larger invertebrate and vertebrate fauna – were recorded with a total station. All excavated materials were wet-sieved through 4 mm and 2 mm mesh and (a sample) through 1 mm mesh.

2.2 Laboratory Methods

Accelerator mass spectrometry (AMS) radiocarbon age determinations on charcoal and shell were undertaken at the University of Waikato Radiocarbon Dating Laboratory and the Australian Nuclear Science and Technology Organisation (ANSTO). Conventional radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsay, 2009) and the SHCal13 (Hogg et al., 2013) and Marine13 dataset (Reimer et al., 2013), with a regional ΔR of 109 ± 25 ^{14}C years for marine samples calculated as part of this study (see Table 1). Details of radiocarbon sample preparation and calibration procedures are

provided in Appendix A1.1. All calibrated ages are reported at the 95.4% probability range. Optically stimulated luminescence (OSL) samples were analysed at University of Adelaide's Prescott Environmental Luminescence Laboratory (Ad14030 to Ad14036) and at the Oxford Luminescence Dating Laboratory (L008/15-1 to L008/15-3). Details of sample preparation and calibration for OSL dating analyses are provided in Appendix A1.2. Bayesian analysis using a Sequence depositional model (Bronk Ramsey, 2008) with an embedded Outlier Model (General t-type) analysis (Bronk Ramsey, 2009) was used to provide the most probable chronology. The dated determinations were grouped in the model using four phases, namely SUs 2, 3, 5 and 6–8. Given some intra-phase off-sets between the radiocarbon and OSL chronologies (see Tables 2 and 3), modelling them as depositionally ordered Phases is the most conservative approach. Phases assume that the dates they contain are uniformly distributed with no order (Bronk Ramsey 1998). Full details of Bayesian analyses are provided in Appendix A1.3.

Sedimentological analyses included particle size analyses (Appendix Fig. A10), micromorphological analyses (refer Appendix A1.4; Appendix Fig. A8 and A9) and mineral determinations (detailed in Ward et al. in press). Teeth, cranial and post-cranial vertebrate specimens were identified to their lowest taxonomic level through comparison to skeletal reference collections held at the Western Australian Museum and the University of Queensland Archaeology Fauna Laboratory (refer Appendix A1.5). Shellfish from the 4 mm sieve fraction were identified to the lowest taxonomic level and quantified by weight, number of identified specimens (NISP) and minimum number of individuals (MNI) (refer Appendix A1.6). Charcoal analysis was undertaken by comparing anatomical features to a regional wood anatomy database and charcoal reference collection (refer Appendix A1.7). Stable isotope analyses were carried out on archaeological and modern tooth samples from the spectacled hare wallaby (*Lagorchestes conspicillatus*) and euro (*Macropus robustus*) from Barrow Island (refer Appendix A1.8). Collectively these analyses represent a comprehensive palaeoenvironmental and archaeological database for Barrow Island, with analyses from other excavation squares still ongoing.

3.0 Results

Wet-sieving of c. 20 m^3 of excavated cultural deposits through nested 4, 2 and 1 mm sieves and flotation recovered rich assemblages of terrestrial and marine fauna, stone artefacts made from local and imported exotic materials, shell implements and ornaments, and some macrobotanics. The deepest excavation level with *in situ* cultural remains is dated to between 51.1–46.2 ka (Fig. 3 and Table 3). Foragers transported four species of marine mollusc, sometimes over 20 km inland, from the Pleistocene coastline to Boodie Cave. Three of these species are dietary and one is utilitarian. While these early marine assemblages are small, they are present consistently throughout the terminal Pleistocene units, indicating that the procumbent shelf was productive during lowered sea stand and continued so into the mid-Holocene (D'Alpoim Guedes et al., 2016; Erlandson and Braje, 2015; Ishiwa et al., 2016; Ward et al., 2015).

Table 1. Details of live-collected shell specimens analysed from the Montebello Islands and northwest Australia and ΔR results. SF=suspension feeder. H=herbivore. C=carnivore.

Museum ID	Species	Collector	Live-Collection Date	Diet	Lab. No.	CRA + Error	Marine Model Age	ΔR
C49667/1	Limidae: *Lima vulgaris* (Link, 1807)	P.D. Montague	29/05/1912-29/08/1912	SF	Wk-43831	560±20	448±23	112±20
C49676/1	Veneridae: *Tapes literatus* (Linnaeus, 1758)	P.D. Montague	29/05/1912-29/08/1912	SF	Wk-43830	582±22	448±23	134±22
S70997	Veneridae: *Dosinia japonica* (Reeve, 1850)	West Collection	1906	SF	Wk-44015	523±24	449±23	74.2±24
C49683/1	Neritidae: *Nerita albicilla* (Linnaeus, 1758)	P.D. Montague	29/05/1912-29/08/1912	H	Wk-43829	837±20	448±23	389±20
C49682/1	Turbinidae: *Turbo laminiferus* (Reeve, 1848)	P.D. Montague	29/05/1912-29/08/1912	H	Wk-43832	578±20	448±23	130±20
C.56886	Volutidae: *Melo amphora* (Lightfoot, 1786)	A.A. Livingstone	00/09/1929	C	Wk-43833	490±20	453±23	37±20
C62096	Volutidae: *Melo amphora* (Lightfoot, 1786)	"Stanley Fowler"	27/03/1944	C	Wk-43834	542±20	463.2±23	79±20
C42530	Volutidae: *Melo amphora* (Lightfoot, 1786)	H. Basedow	00/05/1916	C	Wk-43836	523±27	448±23	75±27

Table 2. Conventional and calibrated AMS radiocarbon ages for Boodie Cave. C = charcoal, S = shell. Isotopic results were standardised to the Vienna PeeDee Belemnite (VPDB) and reported in per mil (‰).

							Depth			Cal			Cal 95.4%	
Code	Item	Species	Fraction	SQ	XU	SU	cm	δ13C[1.]	BP	μ	σ	m	From	To
OZU236	C	N/A	2mm	A102	264	7	111	-27.1 ± 0.5	10930 ± 40	12758	37	12753	12827	12699
OZU237	C	N/A	2mm	A102	264	7	111	-24.5 ± 0.5	9095 ± 30	10218	23	10220	10251	10181
OZU238	S	*Melo amphora*	4mm	A102	266	7	118	-2.6 ± 0.5	28040 ± 100	31317	97	31317	31510	31121
OZU239	S	*Melo amphora*	4mm	A103	272	6	100	-0.7 ± 0.5	8705 ± 30	9251	71	9255	9386	9119
WK-40396	S	*Melo amphora*	In-situ	A102	207	3	19	2.59 ± 0.3	6586 ± 22	6979	59	6974	7111	6873
WK-40397[2.]	S	Sea Urchin cf. Euechinoidea	In-situ	A102	207	3	20	-	-	-	-	-	-	-
WK-40398	S	*Tellina cf. virgata*	In-situ	A102	212	3	26	0.29 ± 0.3	6633 ± 26	7040	59	7040	7149	6931
WK-40399	C	N/A	In-situ	A102	213	3	28	N/A	6260 ± 25	7119	69	7109	7248	7009
WK-40400	C	N/A	In-situ	A102	218	5	45	N/A	10939 ± 36	12761	36	12756	12829	12702
WK-40401	S	*Tellina cf. virgata*	In-situ	A103	246	3	35	1.68 ± 0.3	6591 ± 21	6986	59	6981	7115	6880
WK-40402	S	*Tellina cf. virgata*	In-situ	A103	251	5	52	0.22 ± 0.3	27745 ± 220	31177	142	31173	31463	30892
WK-40403	C	N/A	In-situ	A103	258	6	79	N/A	20853 ± 102	25090	192	25111	25438	24648
WK-42541	C	N/A	In-situ	A103	285	9	163	N/A	12230 ± 39	14076	72	14077	14224	13934
WK-42542	S	Neritidae sp.	In-situ	A103	280	8	138	5.65 ± 0.02	37506 ± 655	41478	548	41510	42525	40331
WK-42543	S	Neritidae sp.	In-situ	A102	268	8	134	4.75 ± 0.02	35294 ± 476	39369	524	39340	40440	38405

1. Note ANSTO $\delta^{13}C$ values represent fractionated values not environmental values and are used for ^{14}C correction only.

2. Undated because sample was recrystallised.

Table 3. Summary of the Boodie Cave optical dating results and final age estimates.

Lab code	SU	Depth (cm)	Grain size (µm)	Water content (%) [a]	Total dose rate (Gy / ka) [b]	Accepted / measured D_e values [c]	Overdis-persion (%) [d]	D_e age Model [e]	Equivalent dose (D_e) (Gy) [f]	Age (ka) [f, g]
Ad14030	2	5	212–250	3.5 ± 0.9	0.49 ± 0.03	48 / 600	41 ± 5	MAM-3	1.5 ± 0.1	3.1 ± 0.3
Ad14031	3-5	24	212–250	12.8 ± 3.2	0.87 ± 0.06	100 / 400	47 ± 4	CAM	11.3 ± 0.6	12.9 ± 1.2
Ad14032	5	68	212–250	10.4 ± 2.6	1.32 ± 0.08	72 / 300	23 ± 3	CAM	23.9 ± 0.8	18.1 ± 1.2
L008/15-3	5	47	180–250	12.5 ± 3.1	1.52 ± 0.11	98 / 500	46 ± 4	CAM	27.4 ± 1.4	18.0 ± 1.6
Ad14033	6	94	125–180	10.2 ± 2.6	1.70 ± 0.10	144 / 800	36 ± 3	CAM	72.5 ±.2.4	42.5 ± 2.9
L008/15-1	7	112	180–250	12.5 ± 3.1	1.71 ± 0.12	93 / 200	55 ± 5	CAM	87.4 ± 5.2	51.1 ± 4.9
Ad14034	7	142	212–250	18.4 ± 4.6	2.22 ± 0.15	60 / 400	31 ± 4	CAM	106.4 ± 5.3	48.0 ± 4.1
L008/15-2	8	138	180–250	12.5 ± 3.1	1.77 ± 0.13	89 / 200	57 ± 5	CAM	95.5 ± 5.7	53.9 ± 5.3
Ad14035	8	169	212–250	13.2 ± 3.3	2.51 ± 0.15	65 / 500	28 ± 4	CAM	123.4 ± 5.3	49.2 ± 3.8
Ad14036	9	193	212–250	7.3 ± 1.8	1.34 ± 0.08	42 / 300	26 ± 4	CAM	103.6 ± 5.4	77.2 ± 6.1

[a] Field water content, expressed as % of dry sediment mass and assigned relative uncertainties of ±25%.

[b] External dose rates were calculated using high-resolution gamma spectrometry for samples Ad14030 to Ad14036, and inductively coupled plasma mass spectrometry for samples L008/15-1 to L008/15-3. The total dose rates include an assumed internal dose rate of 0.03 Gy / ka with an assigned relative uncertainty of ±30%, and a cosmic-ray dose rate estimate calculated using a previous approach (33) with an assigned a relative uncertainty of ±10%.

[c] Number of D_e measurements that passed the SAR quality assurance criteria / total n95umber of grains analysed.

[d] The relative spread in the D_e dataset beyond that associated with the measurement uncertainties for individual D_e values, calculated using a central age model (43).

[e] CAM = central age model (43), MAM-3 = 3-parameter minimum age model (43).

[f] Mean ± total uncertainty (68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.

[g] Total uncertainty includes a systematic component of ±2% associated with laboratory beta-source calibration.
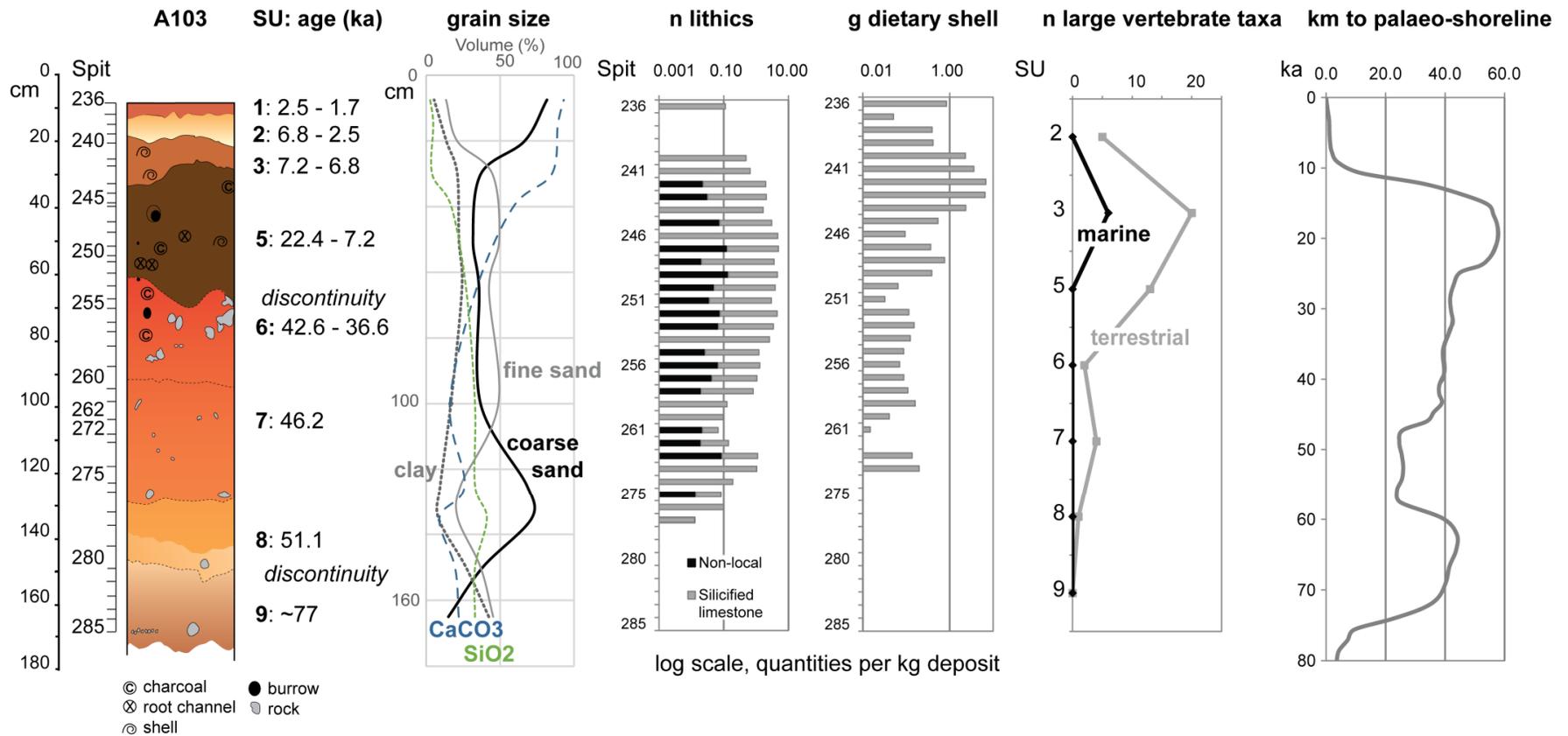
Figure 3. Stratigraphic profile of square A103 at Boodie Cave, with Bayesian modelled age estimates for stratigraphic units (table A5) and changes through the deposit, by spit, in sediment composition and abundance of lithic artefacts, dietary shell and vertebrate taxa. Bayesian analysis groups SU6, SU7 and SU8 together, so the following modelled ages provide the best estimate for their individual ages: SU6 and SU8 are dated by the modelled boundary ages of the group, and SU7 is dated by the modelled age of OSL date L008-15.1. A modelled age within SU6 (date Ad-14033) suggests the SU began forming by 42.6 ka. The particle size analysis curves show coarse sand (particles 355 µm–2 mm diameter), fine sand (63–355 µm), and clay (<63 µm). Vertical scales on different graphs reflect sampling procedures: by depth for sediments, spit (or Excavation Unit) for lithics and shell, and Stratigraphic Unit (SU) for vertebrate taxa. Distance to the palaeoshoreline is shown on a chronological scale.

3.1 Sedimentology

Located 22 m above sea level, excavation squares A102 and A103 preserve a 180 cm deep cultural deposit composed of nine stratigraphic units (SUs; Fig. 3). This sequence is unusually deep and well-stratified considering there is no mid-to-late Holocene contribution due to abandonment of the island. The lowest stratigraphic unit, SU9, is culturally sterile with silt- and clay-rich sediments consistent with a closed cave system. SU8 and SU7 contain the earliest cultural remains and have a dominant coarse sand component. SU6 and SU5 cover the period of lowest sea levels when reworking of sediments across the exposed coastal plain would have concentrated more resistant minerals with high proportions of quartz and low carbonate values (Fig. 3; see also Ward et al. in press). As sea levels rose over an increasingly steep continental shelf (Fig. 1), coastal dunes would have developed closer to Barrow Island, leading to the increase in carbonate in the uppermost sediments of SU5. Quantities of marine shell increase from SU6 to SU5 reflecting the increasing proximity of the coast (Fig. 3). The uppermost units SU3–SU1 are composed of unimodal coarse carbonate sands, with low quartz content, indicating proximal coastal sources. Alongside more detailed mineralogical analyses (see Ward et al., in press), these depositional trends track changes in the position of the cave relative to an expanding and retracting coastal plain.

Small roots and insect burrows were noted in the profile, with some disturbance from single tree roots and fine rootlets concentrated in the northeast and northwest walls. Despite this localised disturbance, the overall integrity of the excavated deposits is high, particularly at the front of Boodie Cave where the lithological interface between units (distinguished by sediment colour, texture and content) is often quite marked (Veth et al., in press). Inside the cave, the unit interfaces are visible, albeit blurred by post-depositional processes, with grain size and micromorphological analyses clearly differentiating unit lithology. Macro- and micro-scale reworking by both flora and soil fauna is evident from infilled small burrows and excremental fabrics and aggregates particularly in Units 5–8 (Appendix Table A9). Pedogenic iron and manganese oxides are concentrated in the mid and lower parts of the profile. Secondary calcite around some bones at the macro- and micro-scale (Appendix Fig. A8F) indicates calcite dissolution and re-precipitation in the middle units (Units 5–6). Secondary gypsum (Appendix Fig. A8D) is concentrated in the upper part of the profile around Unit 3 on the East, South and West walls. Overall pedogenic development is low and decreases upwards through the profile, with syn-depositional sediment disturbance generally less than 5 cm deep, providing independent support for the integrity of the archaeological assemblages with this matrix (Fig. 3).

3.2 Chronology

3.2.1 Marine reservoir effect

For this study we calculated a new regional ΔR value for the Montebello Islands/Barrow Island area of 109 ± 25 ^{14}C years on the basis of AMS analysis of three suspension-feeding bivalves live-collected in the nearby Montebello Islands between AD1906 and AD1912 and housed in the Australian Museum and Western Australian Museum (Table 1). This value is similar to a generalised ΔR of 60 ± 38 ^{14}C years (O'Connor et al., 2010; Squire et al., 2013; Ulm, 2006), which characterises ^{14}C activity in the Leeuwin Current from analyses of recent corals and early twentieth century live-collection suspension-feeding bivalves. Although we consider these values robust for suspension feeding bivalves from the recent past, there are few data available to assess variability in marine reservoir effects in the distant past under different global ocean circulation conditions. Squire et al. (2013) found that ΔR values have been stable over the last 3000 years in the Houtman-Abrolhos Archipelago under the influence of the Leeuwin Current, c.900 km south of Barrow Island. On the northeast coast of Australia, Hua et al. (2015) documented stable marine reservoir values back to the mid-Holocene and then up to ∼410 years in ΔR variability between ∼5500–8000 BP (similar to findings from the southwest Pacific) (Komugabe-Dixson et al., 2016). The magnitude of past reservoir variation in the tropical zone where Barrow Island is located is likely to be relatively small. Modelling of shell radiocarbon ages from Boodie Cave, using the Reservoir Age Database (Franke et al. 2008) (http://www.reservoirage.uni-bremen.de/), accord with those derived from Marine13 (Reimer et al., 2013) under both present-day ocean circulation conditions and assuming 30% reduced Atlantic meridional overturning circulation. Additional studies were undertaken of live-collected deposit feeders, carnivores and algal grazers indicating significant depletion of ^{14}C activity in some specimens (see Table 1 and Appendix A1.1.2).

3.2.2 Radiometric and luminescence results

Radiometric and luminescence dating programs by four independent laboratories (University of Oxford, University of Adelaide, University of Waikato and ANSTO) provide largely consistent chronologies across 10 excavation squares including the two reported on here (Fig. 3). Optically-stimulated luminesence (OSL) dating samples were taken from the South (A102) and North (A103) walls, with overdispersion values between 41–57% indicating some post-depositional mixing in Units 2, 5, 7 and 8 (Appendix Table A4). The lowest stratigraphic unit analysed, SU9, was dated by OSL to greater than 70 ka and is culturally sterile. It contains a significant marsupial rodent component likely from a period when the cave had a more restricted entrance. The lowest stratigraphic unit with cultural materials (SU8) is dated by the Sequence depositional model from 51.1 ka (Fig. 4) and contains small quantities of burnt bone, shell and lithics (Fig. 3).

The dates from SU8–7 in A102 and A103 occur relatively close together in time, with Bayesian analysis conservatively placing the first phase of human occupation of Boodie Cave between 51.1 and 46.2 ka (Fig. 4; Appendix Table A5). Occupation continued throughout the deposition of SU6, ending by 36.6 ka. SU7 contains sizeable stone artefact assemblages and food remains in all sieve fractions. SU6 has mixed terrestrial and marine dietary assemblages containing four species of molluscs; *Nerita*, *Tellina*, *Terebralia* and *Melo*.

A chronological discontinuity following this period coincides with the LGM, and is a common phenomenon in desert lowlands of the Southern Hemisphere (Barberena et al., in press; Veth et al., in press). Following the discontinuity, marine fauna increase markedly during SU5, dated to 22.4–7.2 ka, and coincident with the onset of the Indonesian-Australian Summer Monsoon and rapid sea level rises associated with Meltwater Phase 1A (Denniston et al. 2013). Occupation in SU3 is dated to 7.2–6.8 ka and is followed by abandonment of the island. SU2 and 1 are largely sterile and cover 6.8 to 2.5 ka.
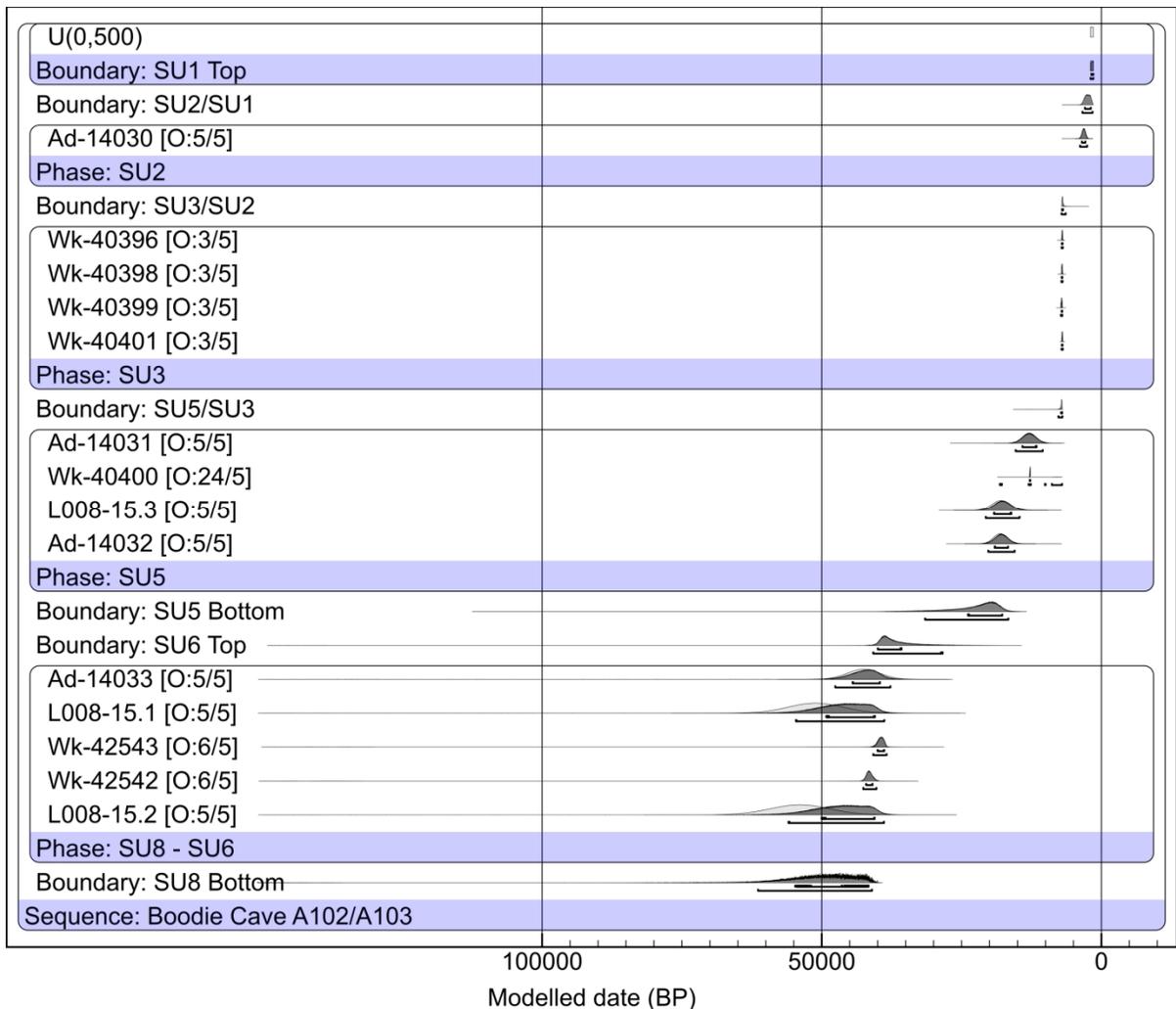
Figure 4. Modelled ages of dates from squares A102 and A103, Boodie Cave, based on Bayesian analysis following removal of outliers (Appendix Table A5).

3.2.3 Bayesian analysis and interpretation

Results of initial Bayesian analysis suggest the first cultural stratigraphic unit began accumulating at 53,352 ± 6,883 cal BP and, despite large OSL error margins, the estimated ages for SUs 8–6 support a conservative case for the beginning of Boodie Cave's human occupation at 50 ka (Appendix Table A6). However, two outliers significantly influence the model: Wk-40402 and Wk-40403. They return low agreement indices and convergence values and have a significant probability of being outliers. To improve chronological resolution, these outliers were removed and the model was re-run (Appendix Table A5). The resulting model supports three major phases of occupation at Boodie Cave: 51,141–36,594 cal BP, 22,393–7,215 cal BP and 7,215–6,850 cal BP. Several aspects of these results require comment. First, given the age of Ad14033 in SU6, SUs 7–8 are certainly older than the modelled age of 42.5 cal BP (Appendix Table A5) and it is possible that SU6 is also older. Second, it is possible that the Neritidae ages (Wk-42542 and Wk-42543) in SU8 are at the radiocarbon barrier (for a similar example concerning terrestrial egg

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shell compared to OSL determinations, see Miller et al., 2016). Since these two age determinations are included in the model (Table A5), it is possible that SUs 8–6 are older than modelled. These dates should be regarded as minimum ages. Finally, given the ages of the rejected samples, it is possible that Boodie Cave retains deposit that falls between (and not within) these age ranges. Overall, however, Bayesian modelling of AMS and OSL results from four independent laboratories provide a robust chronology with a modelled Agreement Index (A_{model}) of 88.6%, a posterior Outlier probability of 94.6% and a correspondence value of 96.3% for these age estimates. These exceed required thresholds (Bronk Ramsey, 2008, 2009).

3.3 Faunal Assemblages

By 42.5 ka, coastal foragers targeted a suite of four molluscan taxa, three of which are dietary (*Terebralia*, *Tellina* and *Nerita*). These taxa come from mangrove, mudflat and rocky substrates. The fourth species (*Melos* sp.) is a well-described, robust mollusc used for water carriage, ornamentation and shell artefact production (Balme and Morse, 2006). The earliest directly dated *Nerita* specimen is 42,550–40,350 cal BP (2 sigma, 98% confidence range; with a modelled age 42,580–40,223 cal BP at 95.4% confidence). Shell weights from the earliest units are low and likely reflect the significant distance specimens have been transported. *Nerita* and *Tellina* have high flesh to shell weight ratios, likely making them attractive targets in this mobile scenario. Along with *Terebralia,* they could have been safely transported in wet clumps to Boodie Cave, which at times lay well over 20 km inland from the Pleistocene shoreline.

Boodie Cave contains numerous modified shell fragments from *Melo* sp. and *Tridacna* sp., including dentate fragments consistent with marine mammal butchering knives; adzes, chisels and polished edge scrapers (Appendix Fig. A12c). The presence of shell tools is expected given the distance from mainland stone artefact sources. There are also incised plaques and 22 fragments of tusk shell (*Dentalium*) with edge notching and wear, which probably served as personal ornaments such as necklaces (Appendix Fig. A12d). These beads are directly dated to 12 ka, consistent with a long chronology of ornament manufacture from these shells (Balme and Morse, 2006).

Prior to the LGM, terrestrial fauna from Boodie Cave are dominated by arid zone species, including the spectacled hare wallaby (*Lagorchestes conspicillatus*) and euro (*Macropus robustus*). These larger macropods are consistent with prey targeted by hunting parties that may have used the cave as an inland bivouac. During the Post-LGM, with rising sea levels and a more proximate coastline, the overall diet expands significantly to include 40 molluscan and 13 terrestrial species. The latter comprise largely small-to-medium game consistent with foraging by family groups. Early Holocene assemblages prior to abandonment by 6.8 ka are exceptionally rich and contain significant quantities of marine fauna including fish, turtle, marine mammal, crab and sea urchin, and over 40 species of marine molluscs. A dense discard layer has been dated in these squares from the front of the shelter to 8.0–7.0 ka (Veth et al., in press). This layer has hearths, translocated hearth stones, turtle bone and marine mammal bones *in situ*.

3.4 Vegetation Structure and Palaeoclimate

Anthracological identifications from hearth charcoal, isotopic analysis of macropod tooth enamel and speleothem records, all generated as part of BIAP, provide additional evidence for a fluctuating shoreline and a gradual transformation from lacustral to arid conditions through time (De Deckker et al., 2014; Denniston et al., 2013). Uranium-thorium dating of stalagmites sampled from Ledge Cave near Boodie Cave indicates wetter conditions on Barrow Island which are broadly consistent with MIS stage 5 lake expansions on the Australian mainland and gradual drying out after 80 ka (Cohen et al., 2012; Magee et al., 2004). Oxygen isotope values for excavated macropod teeth samples register a shift towards increasing aridity entering the LGM (0.44‰ to 3.57‰) compared to the more humid values recorded for modern populations (-1.91‰ to 0.20‰) (Appendix Fig. A14). Tree species identified as fuel within SU6, such as ranji bush (*Acacia pyrifolia*) and gums (*Eucalyptus* spp.) indicate that wood collection occurred along watercourses before the LGM. Following the LGM, in SU5, charcoal from coastal trees such as wirewood (*Acacia coriacea*) and wattle (*Acacia startii*) was recovered (Appendix Fig. A13). Also in SU5, the presence of white mangrove (*Avicennia marina*) and ribbed mangrove (*Bruguiera exaristata*) indicate that established tidal zones were exploited close to the cave. Unlike shellfish, it is unlikely that fuelwood was transported more than several kilometers. The terminal Pleistocene-early Holocene shellfish and macrobotanical records demonstrate the presence of mangroves on nearby coastlines.

3.5 Lithic Assemblages

The flaked stone artefact assemblage from A102 and A103 comprises 6,002 artefacts, with the majority manufactured from local limestone and calcrete (Appendix Fig. A15). Only 113 artefacts are manufactured from non-local lithologies. The closest known sources for the latter are on the mainland (Fig. 1). The limestone assemblages reflect the manufacture of large flakes (with macroscopic retouch or edge damage on less than 10%), which were used in place of exotic materials. In contrast, c.40% of the non-local raw material (such as quartz and silicified sedimentary lithologies) has evidence for retouch and edge damage. Stone artefacts are abundant in all deposits, dated between 51.1 and 6.8 ka (Fig. 3). Contrasting with the cave assemblages, the flaked and ground stone artefacts recorded from the 30 open sites derive from non-local sources and show levels of retouch and utilisation ranging from 15% to 40% – much higher levels than registered from mainland open surface scatters. The high level of re-use on non-local stone in all Barrow assemblages suggests long-distance transport when the island was connected to the mainland and when the coast was relatively distant. The dominance of exotic lithics in the open sites may reflect a functionally or temporally distinct terrestrial pattern not registered in the Boodie Cave stratigraphic sequence, such as the LGM lacunae.

4.0 Discussion of a coastal desert adaptation

The Boodie Cave assemblages register first occupation of the now-drowned North-West Shelf between 51.1–46.2 ka and this timing is consistent with other early dated assemblages from Sahul (e.g. Clarkson et al., 2015;p Hamm et al., 2016; Wood et al., 2016). The cave has evidence for repeated occupation, with a discontinuity straddling the LGM and then abandonment by 6.8 ka when the island becomes separated from the mainland (Veth et al., in press). This is the same date at which the nearby Montebello Islands are also abandoned and is likely a function of distance offshore and island biogeography (Veth et al., 2007). The earlier stratigraphic units are dominated by larger arid zone macropods, such as the spectacled hare wallaby and euro. Their presence is consistent with prey targeted by hunting parties who may have used the cave as an inland bivouac. Four shellfish species are also present by 42.5 ka and include gastropods such as *Nerita* and *Terebralia* that could be transported over the Pleistocene coastal plain. These represent the oldest marine dietary remains in Australia.

Previous modeling of the productivity of Australian coastal plains (e.g. Beaton 1995) has predicted that the coastline was highly variable as a resource zone for hunter-gatherers due to fluctuations between precipitous versus procumbent shelves, and differences in coastal complexity between LGM lowstand compared to after sea level stabilisation. In contrast, our revised modelling predicts that around the LGM and throughout the period of transgression, the exposed North-West Shelf was productive for humans due to the tidal ranges that were as larger than present, resulting in extensive exploitable intertidal habitats (Ward et al., 2013, 2014, 2015). The early dietary shellfish assemblages from Boodie Cave, and recent cores capturing estuarine shellfish at the LGM off the Bonaparte Basin (Ishiwa et al., 2016), increasingly lend support to this modelling. Particularly prevalent from after 42.5 ka until abandonment of Barrow Island, is the estuarine gastropod *Terebralia*, indicating mangrove habitats were present throughout this period. Consistent with recent biome modelling from East Asia (D'Alpoim Guedes et al., 2016), a range of productive habitats were accessible to human foragers on the exposed shelf. Marine molluscs were unquestionably transported long distances, and at times from 10 to 20 km across the Pleistocene coastal plain, and processed at Boodie Cave. Other marine mollusc species would very likely have been processed and consumed closer to the coastline (Bird et al., 2002; Jazwa et al., 2015; Waselkov, 1987). This record indicates that marine resources were available and repeatedly taken as food and artefacts during foraging trips inland across the arid coastal plain to Boodie Cave.

By the early to mid-Holocene, species breadth expands to include over 17 small-to-medium-sized terrestrial taxa. Rich assemblages of turtle, marine mammal, large fish, sea urchin, crab and 40 species of molluscs are dated to approximately 8–7 ka when the site likely functioned as a residential base on the proximal coast. Tusk shell bead segments have been direct dated to 12 ka while a variety of modified baler, *Syrinx* and *Tridacna* implements date to the early Holocene. The pronounced change in dietary remains reflects the changing position of the coast and the social composition of forager groups, and is supported by sedimentological evidence of this transgressing coastline (Ward et al., in press). The early appearance of dietary shellfish in the

Boodie Cave assemblages and their presence until abandonment of the island supports our modelling for continuing productivity of the Pleistocene coastline for coastal foragers (D'Alpoim Guedes et al., 2016; Manne and Veth, 2015; Ward et al., 2013, 2014, 2015).

While the earliest evidence for marine resource use may lie underwater, this current research serves to characterise the submerged cultural landscapes of the larger North-West Shelf (Manne and Veth, 2015; Ward et al., 2013, 2014, 2015, 2016; Brooke et al., 2017).

5.0 Conclusions

Boodie Cave contains dated stratified cultural deposits which document the early occupation of the maritime deserts of North-West Australia. The earliest dates for occupation of Boodie Cave, based on results from four laboratories and subject to Bayesian modelling, are 51.1– 46.2 ka. These overlap with the set of early dates now widely accepted for the early occupation of Australia. There are direct dates on Neritidae gastropods from 42.5 ka and assemblages of shellfish dating to before and after the LGM. Dietary breadth increases substantially by 7 ka to include 40 species of molluscs with the addition of marine mammals, large fish, and turtle with hearth stones. The earlier units contain larger macropods and, following the LGM, show an increase in species breadth with a greater inclusion of small-to-medium-sized marsupials, lizards, and snakes.

Combined with our new climate data derived from speleothems, charcoal and isotopic analyses of tooth enamel, we interpret the dietary remains as reflecting an early and continuing arid zone adaptation with an initially minor coastal marine resource signal. This minor marine signal is almost certainly a function of the distance to the coastline at this time, where molluscs were required to be transported over 10 to 20 km across the Pleistocene coastal plain. The marine assemblages effloresce when the coast becomes proximal (within several kilometres) from the cave mouth.

We conclude that these early foragers of the North-West Shelf coastal deserts were engaged in mobile configurations linking the resources of the coast with those of the arid hinterland. This is argued to be one of the signatures of human adaptation to coastal deserts in the Southern Hemisphere (Barberena et al., in press). This dynamic record ceases when sea level stabilises by 6.8 ka and the island is positioned 60 km from the present-day coastline. Abandonment of Barrow Island and the lack of evidence for re-incorporation by watercraft-using peoples after this date, likely reflects its significant distance off-shore and size, and is consistent with models of human island biogeography within Australian waters.

Detailed analyses of cultural assemblages in their stratigraphic context along with the use of four independent dating laboratories, has provided a robust and plausible scenario for first occupation of the continent before 46.2 ka and as early as 51.1 ka consistent with increasing evidence from northern Australia (Clarkson et al., 2015; Hamm et al., 2016; Wood et al. 2016).

The Barrow Island evidence supports models that posit that the first anatomically modern humans radiating along the southern arc out of Africa had advanced maritime competencies (Erlandson and Braje 2015). The record also illustrates that people rapidly incorporated arid zone faunas into their dietary assemblages as part of what we term a *maritime desert adaptation* (Bird et al. 2016; Hamm et al. 2016; Veth et al. 2014). The Boodie Cave assemblages are globally significant in providing direct evidence for the lifeways and subsistence of people adapting to early desert landscapes. Although there are well-dated Middle Palaeolithic sites in other arid regions such as the Saharo-Arabian belt and the Thar Desert, there is a lack of subsistence information from these sites, and it is unknown how and when people adapted to these ecologies (Blinkhorn et al. 2017; Boivin et al. 2016; Breeze et al. 2017). Boodie Cave provides significant new evidence that humans in the Late Pleistocene had such abilities and indeed that these included both maritime and desert components.

These findings have significant implications for new understandings about the maritime competencies of modern humans dispersing along the southern arc from Africa to Australia. They address the complete lack of direct evidence for seafaring, shell middens, and coastal occupation spanning the entire distance from East Africa, the Arabian Peninsula and the Indian subcontinent where low visibility and poor preservation have unquestionably suppressed the record. The presence of dietary shellfish from the earliest occupation units of Boodie Cave, as well as now from reliably dated sites in East Timor and Borneo (O'Connor et al. 2011; Barker 2013) provide irrefutable evidence for maritime competencies at the end of the Southern Dispersal Route (Kealey et al. 2016). These sites support models for modern humans dispersing rapidly out of Africa along maritime corridors (Erlandson and Braje 2015). Remarkably the early colonists of the now-submerged shelf of Greater Australia did not turn their back on the sea or remain coastally tethered but rather rapidly adapted to the new marsupial animals and arid zone plants of the extensive maritime deserts of North West Australia.

Acknowledgments

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