U-series evidence for widespread reef development in Shark Bay during the last interglacial

Michael J. O'Leary^{a,b,*}, Paul J. Hearty^c, Malcolm T. McCulloch^d

^a School of Earth and Environmental Science, James Cook University, Townsville QLD 4811 Australia

^b Department of Environmental and Geographical Sciences, Manchester Metropolitan University, Manchester, M1 5GD, United Kingdom

^c School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

^d Research School of Earth Sciences, Australian National University, Canberra, ACT, 0200, Australia

Received 4 July 2007; received in revised form 27 September 2007; accepted 9 October 2007

Abstract

Field observations and U-series ages reveal that Shark Bay, Western Australia (WA) has been inundated by the sea on at least three occasions during the Late Pleistocene/Holocene, resulting in a succession of marine deposits around the Bay. The exact age of these deposits has until now been problematic due to a lack of reliable and accurate age data. This study reports 16 new U-series coral dates from emergent reef deposits around Shark Bay, and point to an extended period of coral reef development during the peak of the last interglacial, marine isotope stage (MIS) 5e. This is attributed to enhancement of marine circulation within the reaches and basins, a result of higher sea levels and an absence of major sill and bank structures. Stromatolites are absent from the geological record within Shark Bay until the late Holocene, suggesting that sea levels and marine sedimentary processes that have operated during the present sea-level highstand are unique to this period. There is little direct evidence of fossil reef development occurring during interglacials of the middle/late Pleistocene (MIS 9/11).

© 2008 Published by Elsevier B.V.

Keywords: Shark Bay; Stromatolite; Reef; U-series; MIS 5e; Hypersaline

1. Introduction and environments

Present-day Shark Bay on the central west coast of Australia (24.5° to 26.5° South latitude) has a depauperate (to non-existent in inner bay waters) coral fauna when compared to Ningaloo reef in the north and the Houtman–Abrolhos in the south (Fig. 1A). The presence of large barrier islands to the east and north, as well as the

length and shallowness of the embayments, restricts oceanic circulation within Shark Bay (Logan and Cebulski, 1970). As a result, permanent high salinities and steep temperature gradients limit the occurrence of modern coral growth to the seaward margins of the embayments (Marsh, 1990). There is however evidence of reef development, having occurred, well within the present metahaline and hypersaline embayments during previous interglacials (Logan et al., 1974).

Although limiting present-day coral growth, the hypersaline environments such as those present today in Hamelin Pool and L'Haridon Bight, Shark Bay, are ideal for the development of microbial communities

* Corresponding author. Department of Environmental and Geographical Sciences, Manchester Metropolitan University, Manchester, M1 5GD, United Kingdom. Fax: +44 161 247 6318.

E-mail address: m.oleary@mmu.edu.au (M.J. O'Leary).

Fig. 1. A) Map of Australia showing location of three principal reef growing regions along the West Australian coast including; Ningaloo Reef (Cape Range) 21°–23° S, Shark Bay (study location), 24.5–26.5° S and the Houtman Abrolhos (island group) 28° S. B) Location Map of Shark Bay. Salinity contours for in parts per thousand (ppt). Thick black lines represent areas of extensive stromatolite growth. Open circles show location of Pleistocene reef outcrop with U-series date. Black stars indicate presence of living corals (modified from Marsh, 1990). Black diamonds represent other known exposures of emergent Pleistocene marine deposits. Note the proximity of emergent Pleistocene marine outcrops with present Holocene shoreline.

responsible for building stromatolites. Although they are amongst the oldest form of life, being recorded back to the early Archean, stromatolites have a limited present-day occurrence, being restricted to a few other hypersaline lakes along the West and South Australian coastlines, and a restricted occurrence in the Bahamas (Andres and Reid, 2006). Thus understanding the evolution of the Shark Bay environment is critical to understanding this unique and once prolific form of life.

The history of the evolution and carbonate sedimentation of Shark Bay is summarised by Playford (1990) and reported in two American Association of Petroleum Geologists (AAPG) Memoirs, (Logan, 1970, 1974). While the sedimentological aspects of both AAPG memoirs are highly detailed and descriptive, the terminology and chronology of the marine highstand events is questionable due to the absence of reliable dating techniques and at that time a more limited understanding of timing and amplitude of Quaternary sea-level change.

The early work of Logan et al. (1974) recognized that marine transgressions had inundated the ancestral dune landscape of Shark Bay three separate occasions during the latter part of the Quaternary. Evidence for these events is revealed in marine carbonate sequences that outcrop along the Shark Bay coastline. These marine transgressions are referred to in order of decreasing age: 1) middle Pleistocene Dampier marine phase; 2) the late Pleistocene Bibra marine phase; and 3) the Holocene–Recent marine phase. An exact chronology of these events has not been previously established; therefore the correlation of carbonate outcrops across the bay has remained problematic (Table 1).

1.1. Coastal landforms

Shark Bay is Australia's largest semi-enclosed coastal embayment with 1100 km of coastline and an open water area of approximately 10,000 km². It is bounded to the west by Edel Land and Dirk Hartog Island, to the north by Bernier and Dorre Islands and to the east by the Australian mainland (Fig. 1B). The Peron Peninsula, a large lower to middle Pleistocene relic transverse dune complex (Hocking et al., 1987) bisects the bay, forming two shallow NW–SE trending reaches, Freycinet Reach and Hopeless Reach. Upper Pleistocene ooid rich carbonates flank much of the peninsula's western headlands (Donald, 2003). The 40-km-long Hopeless Reach in the east has a coastal strip consisting of extensive supratidal flats, and a low-lying coastal plain, backed on the east by a Tertiary limestone escarpment. The adjoining catchment of 49,600 km² feeds two

Table 1

Stratigraphic nomenclature for Shark Bay

Period/epoch	Teichert (1950)	Playford (1990)	Logan et al. (1974)	MIS
Holocene	Coastal Limestone	Tamala Limestone	Holocene–Recent	MIS 1
Last Glacial Cycle			Nilemah Sands Depuch Formation	MIS 2–4
Upper Pleistocene			Bibra Formation Marine deposits	MIS 5a–5e
Middle Pleistocene			Dampier Formation Carbla oolite	MIS 11
Lower Pleistocene			Tamala Eolianite	MIS 11>37
Upper Pliocene			Peron Sandstone	
		Trealla Calcarene		

ephemeral rivers, the Gascoyne and the Wooramel. Fluvial contribution from surface runoff into Shark Bay is severely restricted by low intermittent rainfall (<200 mm/y), high evaporation rates (>2000 mm/y), and porous permeable soils.

The Tamala Limestone (Table 1: Playford et al., 1976), dominates exposures across much of Edel Land, is bounded on the west by the Zuytdorp cliffs, 150 m to 250 m high, which front the Indian Ocean. The coastline along Freycinet Reach consists of partially submerged, north-south orientated, longitudinal dune ridges and interdune valleys. The north-south trending Bernier and Dorre Islands are composed of Pleistocene age carbonate eolianites with large scale cross bedding.

1.2. Oceanography

Seawater exchange between continental shelf waters (including the Leeuwin Current) and Shark Bay waters occurs through the Naturaliste and Geographe Channels, 25 and 35 km wide, 60 and 50 m deep, respectively (Fig. 1B). These channels shoal rapidly to an average depth of 15 m as they enter the bay. During the winter and spring, when the predominantly southerly winds periodically swing to the north, continental-self waters penetrate northern Shark Bay through the Geographe Passage (Burling et al., 1999). Extensive shallow carbonate banks and seagrass beds further restrict circulation within Shark Bay. The largest bank is the

Faure Sill, which effectively divides Hopeless Reach, forming L'Haridon Bight and the larger Hamelin Pool in the south (Fig. 1B). The Herald Loop Channel, 2 km wide 6 m deep, permits limited seawater exchange between the two basins. Restricted marine circulation combined with an annual evaporation rate of 2000 mm, 10 times greater than the annual precipitation, has resulted in strong lateral salinity gradients within Shark Bay. Normal oceanic salinities of 35 to 40 ppt persist in the northern parts of the bay, but this changes to metahaline (40 to 56 ppt) through to hypersaline (56 to 70 ppt) in L'Haridon Bight and Hamelin Pool (Fig. 1B). These extreme salinity values were found to be permanent within Hamelin Pool showing that increased salinity, due to evaporation, is balanced by return circulation into the rest of the bay (Logan and Cebulski, 1970; Burling et al., 1999).

1.3. Shark Bay coral communities

Areas of greatest present-day coral diversity occur along the protected headlands of Bernier and Dorre Islands and to a lesser extent the lee side of Dirk Hartog island, where 55 species from 23 genera form narrow fringing or patch reefs in close proximity to the open sea (Marsh, 1990; Hatcher, 1991) (Fig. 1B). Coral communities are conspicuously absent from northern open waters of Shark Bay where extensive mobile carbonate banks and seagrass beds limit the availability of suitable substrate. However, where scattered hardgrounds are found, generally along the western fringe of Denham Sound, communities of *Turbinaria* dominate (Marsh, 1990). A further reduction in coral diversity occurs within the metahaline regions of Freycinet Reach where minor solitary stands of *Goniastrea aspera*, *Favites pentagona*, *Favia* sp, *Goniopora lobata* and *Turbinaria* spp. are present (Marsh, 1990). Moving into Henri Freycinet Harbour, along Hopeless Reach and into hypersaline Hamelin Pool there are no extant coral communities.

1.4. Shark Bay stromatolite communities

Lithified and laminated organo-sedimentary structures (stromatolites) occur along the intertidal and subtidal shorelines of Hamelin Pool and L'Haridon Bight (Fig. 1B). Their occurrence coincides with ecologically harsh (hypersaline) environments where potential competitors for substrate, such as corals or seagrass (Kendrick et al., 1990), or predators such as gastropods (Playford, 1990), are severely restricted. Vertical accretion of Shark Bay stromatolites, facilitated by sediment trapping, is ~0.5 mm/year (Playford, 1990),

but can be as low as 0.3 mm/year within the higher energy intertidal zone where potential for erosion is increased (Chivas et al., 1990). With such slow accretion rates, there is a likelihood of burial during periods of rapid sediment deposition. However, one of the factors that allow stromatolites to dominate Hamelin Pool and L'Haridon Bight, and is intrinsically linked to hypersaline zones, is the lack of biogenic sedimentation due to a reduced numbers of carbonate producing flora and fauna (Walker and Woelkerling, 1988). Additionally, due to the extremely low tidal velocities, there is little potential for sediment transport; when high-energy events such as cyclones do occur, sediments tend to bypass the intertidal or subtidal zones to form onshore storm ridges of shell debris (Playford, 1990; Nott, 2006).

1.5. Research aims

1. Develop a stratigraphic succession and a chronological framework for emergent marine units in order to establish the frequency, timing and duration of Pleistocene marine incursions into Shark Bay.
2. Provide insight into the evolution of oceanographic processes within Shark Bay, based on timing and emplacement of major morphological features.
3. Offer scenarios and models that might explain the occurrence of stromatolites in the present-day hypersaline environment of Hamelin Pool and the much more widespread distribution of corals within Shark Bay generally during MIS 5e, using modern environmental parameters as a point of reference.

2. Materials and methods

Place names of study sites were derived from the Point Quobba to Geraldton nautical chart (Aus 331), Monkey Mia Special, Yaringa, Wooramel and Carnarvon Special topographic and geologic maps.

2.1. Stratigraphic logs and sample collection

Many previously described (Logan et al., 1974) and several new localities were stratigraphically logged. Elevations of emergent marine units were measured using a theodolite or hand-level, and mean sea level (MSL), calculated from known tidal elevations, was assigned the 0 m benchmark (± 10 cm). The composition of the sedimentary strata both underlying and overlying emergent marine units was described.

Much effort was made to sample corals in the field without bias towards a particular period of coral growth

i.e., sampling at multiple locations around the bay and spatially exclusive points from an outcropping reef. However, it is highly likely that some reef sediments have been eroded (Tetrodon Loop) (Fig. 2A), buried under active dunes or intertidal sand sheets (Gladstone North), or concealed by stromatolite growth (Nilemah) (Fig. 2B). It was envisaged that sampling corals from multiple locations around the bay would reveal a more complete picture of reef development.

2.2. Geochronology and reliability of $^{234}\text{U}/^{230}\text{Th}$ coral ages

U-series measurements were performed using a Neptune MC-ICPMS at the Research School of Earth Sciences, Australian National University. Measurements were conducted using a combination of simultaneous multiple-Faraday cup and ion counter protocols modified from those previously described for TIMS (Stirling et al., 1998; McCulloch and Esat 2000). The

main difference being that ion counter yields were determined by reference to an external standard (SRM 960) for determination of $^{234}\text{U}/^{235}\text{U}$ ratios where ^{234}U is measured using ion counting. For the low abundance isotopes ^{230}Th and ^{229}Th (spike) these were both measured using the central ion counter, but simultaneously with ^{235}U and ^{238}U and ^{232}Th on faraday cups allowing corrections for both beam instability as well as mass bias. For a detailed description of protocols see McCulloch and Mortimer (in press). This multiple-Faraday approach yield higher precision in conjunction with a significantly reduced sample size requirement, lowering age uncertainties by up to a factor of five (Stirling et al., 2001) compared to single cup procedures. For the labour intensive preparation of carefully selected portions of coral walls adopted in this study, the measurement of relatively small samples (<50 mg) is also distinct advantage.

Following the procedures of earlier workers (Chen et al., 1991; Stirling et al., 1995, 1998; Robinson et al.,

Fig. 2. A) Emergent late Pleistocene reef outcrop at Tetrodon Loop observed at low tide. Modern sedimentary and biological processes have eroded or concealed much of the Pleistocene marine record with only a brief time interval accessible for investigation. B) Photo of sample SHP1 collected from Nilemah at the southern end of Hamelin Pool. A modern stromatolite initiated growth atop a Pleistocene coral. This image neatly shows the contrasting environments that persisted at this one location; open marine during the last interglacial and hypersaline during the Holocene sea level highstand. C) Extensive beachrock outcrops, several kilometres north of Monkey Mia. With the bulk of the deposit positioned above the intertidal zone its formation is unlikely to have occurred during the late Holocene sea level still stand. With cemented coral rubble within the beachrock returning U-series ages of around 122 and 125 ka we expect the deposit formed during late 5e with a sea level several metres higher than its present position.

2004) corals were screened for potential U and Th loss or gain based on the following criteria:

- We consider the calculated $\delta^{234}\text{U}_{\text{initial}}$ to be the best quantitative test for open system behaviour in corals (for an explanation of this item, refer to note #4 of Notes to Table 2). For a coral age to be considered strictly reliable $\delta^{234}\text{U}_{\text{initial}}$ values should reflect a modern seawater value of $146.6 \pm 10\%$.
- The total uranium concentration of fossil corals should approximate modern coral values of about 3 ± 0.5 ppm of uranium.
- Fossil corals should be free of allochthonous ^{230}Th , as indicated by the absence of detrital ^{232}Th (< 1 ppb).
- Corals should show 100% primary aragonite structures.

3. Results

A total of 14 U-series measurements of coral ages from various locations around Shark Bay (Fig. 1B) are presented in Table 2. A flowstone sample from the Zuytdorp Cliffs at the Womerangee Hill type section and a stromatolite sample from Nilemah were also dated.

3.1. Baba Head

Baba Head is located on the northeastern headland of Disappointment Inlet (Edel Land) $26^{\circ}60.2'$ S $113^{\circ}69.2'$ E, within the metahaline Freycinet Harbour (Fig. 1B). The lithology of the area was described by Read (1974) as unconsolidated, to strongly-lithified calcarenite with large-scale crossbedding. A wave cut terrace and notch composed of a well-indurated, Mid-Pleistocene, red/yellow oolite forms the basal unit. A well-indurated coquina beach with coral rubble lies unconformably above the terrace at $+0.5$ to $+1.0$ m and partly in-fills the notch. Read (1974) correlated the marine coquina and coral rubble unit with the Bibra Formation. An allochthonous coral fragment from the coquina deposit returned a U-series age of 122.6 ± 5 ka with a $\delta^{234}\text{U}$ value of 151.6% indicating a reliable age (Table 2, SBA_c).

3.2. Tetrodon Loop

Located on the eastern shore of Dirk Hartog Island, Tetrodon Loop, $25^{\circ}57'$ S $113^{\circ}08'$ E is presently within the oceanic marine zone, and downwind of a large mobile

Table 2
U-series data

Sample	U ppm ^a	^{230}Th ppt ^b	^{232}Th ppb ^c	$\delta^{234}\text{U}$ ^d	^{234}U error	$^{230}\text{Th}/$ ^{238}U ^e	Error	$[^{230}\text{Th}/$ $^{232}\text{Th}]$	Age (ka) ^f	Age error	Initial $\delta^{234}\text{U}$ ^g	$\delta^{234}\text{U}$ error	Location
SBA1_c	2.81	34.79	X	107.07	1.10	0.76	0.002	3427.4	122.64	0.56	151.59	1.47	Baba Head
STG5_c	2.88	35.94	0.46	103.81	1.30	0.77	0.003	14766.3	127.00	1.00	148.80	1.75	Tetrodon L
STG1_c	2.46	31.09	0.08	106.57	0.66	0.78	0.003	72614.3	128.80	0.92	153.50	0.96	Tetrodon L
STG4_c	1.99	24.70	0.12	105.73	1.14	0.77	0.002	39536.2	125.40	0.76	150.80	1.50	Tetrodon L
SPI4_c	2.92	35.93	0.28	107.96	1.05	0.76	0.002	23948.4	122.80	0.65	152.90	1.40	Pelican Is
SPI5_c	2.36	28.64	0.59	107.80	0.88	0.75	0.002	9176.7	119.60	0.58	151.30	1.15	Pelican Is
SWO1_c	2.76	35.47	0.07	113.75	1.05	0.79	0.002	90677.5	131.30	0.79	165.20	1.40	Wooramel Cliff
SWR1_c	4.56	77.11	145.30	80.99	0.61	1.05	0.003	99.5	313.00	5.60	196.80	3.05	Wooramel Cliff
SGN1_c	2.22	47.64	261.43	197.30	2.10	1.32	0.008	34.2	127.30	1.10	150.10	2.10	Gladstone N
SGN3_c	3.25	41.08	0.41	116.18	0.72	0.78	0.001	18740.2	126.87	0.47	166.40	0.96	Gladstone N
SMM2_c	2.28	28.43	1.00	109.06	0.97	0.77	0.002	5347.0	125.60	0.75	155.70	1.30	Monkey Mia
SMM1_c	2.77	34.65	0.23	111.61	0.90	0.77	0.002	27790.8	125.20	0.60	159.10	1.20	Monkey Mia
SMM4_c	3.79	46.69	144.53	106.04	0.57	0.76	0.002	60.6	122.94	0.46	150.20	0.76	Monkey Mia
SWG1_f	0.37	3.86	1.67	64.61	1.83	0.65	0.003	432.6	100.80	0.76	86.00	2.30	Womerangee
SHP1_c	3.20	53.36	0.38	85.23	1.61	1.02	0.004	26013.2	283.00	5.35	190	3.5	Nilemah
SHP1_s	2.63	2.66	257.64	146.87	1.45	0.06	0.001	1.9	6.09	0.071	149.4	1.4	Nilemah

^a Uranium concentrations are measured in parts per million (ppm).

^b ^{230}Th concentrations measured in parts per trillion (ppt).

^c ^{232}Th concentrations measured in parts per billion (ppb).

^d $\delta^{234}\text{U} = \{[(^{234}\text{U}/^{238}\text{U})/(^{234}\text{U}/^{238}\text{U})_{\text{eq}}] - 1\} \times 10^3$. $(^{234}\text{U}/^{238}\text{U})_{\text{eq}}$ is the atomic ratio at secular equilibrium and is equal to $\lambda_{238}/\lambda_{234} = 5.4891 \times 10^{-5}$, where λ_{238} and λ_{234} are the decay constants for ^{238}U and ^{234}U , respectively, adopting half-lives of Cheng et al. (2000).

^e $[^{230}\text{Th}/^{238}\text{U}]_{\text{act}} = (^{230}\text{Th}/^{238}\text{U})/(\lambda_{238}/\lambda_{230})$.

^f U-series ages are calculated iteratively using: $1 - [^{230}\text{Th}/^{238}\text{U}]_{\text{act}} = \exp(-\lambda_{230}T) - (\delta^{234}\text{U}(0)/1000)(\lambda_{230}/(\lambda_{230} - \lambda_{234}))(1 - \exp(\lambda_{234} - \lambda_{230}T))$ where T is the age in years and λ_{230} is the decay constant for ^{230}Th . $\lambda_{238} = 1.551 \times 10^{-10} \text{ y}^{-1}$; $\lambda_{234} = 2.826 \times 10^{-6} \text{ y}^{-1}$; $\lambda_{230} = 9.158 \times 10^{-6} \text{ y}^{-1}$. Strictly reliable ages will have $\delta^{234}\text{U}_{\text{initial}} 146.6 \pm 5\%$.

^g The initial value is given by $\delta^{234}\text{U}_i = \delta^{234}\text{U}(0)\exp(\lambda_{234}T)$, where T is the age in years.

dune system (Fig. 1B; Fig. 2A). The only modern coral communities found in the area are those surrounding Egg Island at the northern end of Tetrodon Loop and consist primarily of the genus *Turbinaria*. Emergent fossil reefs outcrop along the western shore and at the head of the Tetrodon Loop and are dominated by *Platygyra*, *Porites* and *Galaxia* species. Reef elevation sits approximately +1.5 to +2.5 m, forming a small erosional scarp. Logan et al. (1974) originally assigned sediments of the Tetrodon reef to the middle Pleistocene Dampier Formation. However, U-series dating of three in situ corals from this study (Table 2) along with two previously dated corals from Stirling et al. (1995) and Stirling (1996) return an average age of 126.5 ± 1.5 ka, placing the age of formation firmly within MIS 5e, and correlating with the marine Bibra Formation. There is a wave cut terrace similar to that at Baba Head, 0.8 m above MSL. The mid-Pleistocene basal unit is well lithified and comprised of red/yellow ooids.

3.3. Gladstone North

The type section of the Bibra Formation, MIS 5e, is located at Gladstone North, a few kilometres south of the Wooramel delta, $25^{\circ} 55.059' \text{ S}$, $114^{\circ} 15.383' \text{ E}$ (Fig. 1B). At this locality in situ *Porites* and Faviidae coral heads outcrop within the intertidal zone but are mostly buried beneath onlapping Holocene sediments. U-series dating of two large in situ coral heads (Table 2, SGN1_c and SGN3_c) returned ages of 127.3 ± 1.1 and 126.9 ± 0.5 with $\delta^{234}\text{U}$ values of 150‰ and 166‰ respectively placing the timing of coral growth during early MIS 5e, although the latter sample has only a marginally acceptable $\delta^{234}\text{U}$ value. The upper surfaces of these corals show no evidence of bioerosion or subaerial exposure, suggesting that they grew below the level of mean low water springs and therefore their elevation do not represent the true maximum MIS 5e elevation of sea-level. The coastal cliffs at Gladstone North are composed of an alternating sequence of bioclastic and ooid rich beach ridge deposits. A coral fragment from the Wooramel Cliff section, ~4 m above MSL at the southern end of the Wooramel delta, returned an age of 313 ka (Table 2, SWR1_c) placing its growth sometime during MIS 9. However, an elevated initial $\delta^{234}\text{U}$ of 196‰ and a ^{232}Th concentration of 145.3 ppb make the accuracy of this age highly questionable.

3.4. Monkey Mia

Continental dunes (Peron sandstone) dominate the western fringe of the Peron Peninsula and form a 6–8 m

high sea-cliff, a result of modern marine erosion. Marine carbonates onlap the shore as Holocene beach and coastal ridge deposits. Beachrock outcrops along a 100 m section of beach approximately 2 km North of Monkey Mia at $25^{\circ} 47.05' \text{ S}$, $113^{\circ} 41.12' \text{ E}$, between 0 and +1.5 m (Fig. 1B; Fig. 2C). Beach rock usually forms within the intertidal zone (Bricker, 1971), its presence above this zone suggests it was formed during a higher than present sea-level event. Early Holocene sea levels in Shark Bay are thought to have been between 0.5 and 1 m above present elevations (Playford, 1990). However, coral rubble cemented within the beach rock returned two U-series ages of 125.6 ± 0.8 ka and 125.2 ± 0.6 ka with $\delta^{234}\text{U}$ values of 155.7‰ and 159.2‰ respectively (Table 2, SMM2_c and SMM1_c).

Beach coquina outcrops at the base of the Peron dunes 2 to 3 m above MSL, 50 m to the north of the beachrock unit. A fragment of the coral *Turbinaria* sp. from within the deposit returned a younger MIS 5e age of 123 ± 0.5 ka, with $\delta^{234}\text{U}$ values of 150.2‰ (Table 2, SMM4_c). The MIS 5e age for the beachrock and coquina beach deposit at Monkey Mia places the MIS 5e shoreline along the Monkey Mia coast in close proximity to the present shoreline, but at 2–3 m higher levels suggesting a stable coastline with little erosion or dune accretion.

3.5. Pelican Island

Pelican Island is an elongate low relief (<3 m above MSL) ooid rich carbonate sand cay situated on the northern edge of the Faure Sill, $25^{\circ} 50.1' \text{ S}$, $114^{\circ} 01' \text{ E}$ (Fig. 1B). An emergent reef outcrops along the intertidal zone with many of the surfaces recolonised by calcareous algae. U-series dating of two corals returned ages of 122.8 ± 0.7 ka and 119.6 ± 0.6 , with $\delta^{234}\text{U}$ values of 152.9‰ and 151.3‰ respectively (Table 2, SPI4_c, SPI5_c), indicating that Pelican Island was a shoal or bank feature during MIS 5e, with coral growth becoming established towards the end of the MIS 5e highstand.

3.6. Nilemah

Nilemah is located at the southern side of Hamelin Pool, in an area of extensive stromatolite growth. A small stromatolite mound (SHP1) was collected from Nilemah prior to the Shark Bay area receiving world heritage status in 1990, was kindly provided by Dr Bob Burne from the Department of Geology, Australian National University. The exact elevation of this sample is unknown except that the stromatolite was collected from within the littoral zone. It was found that the stromatolite grew on top of a Faviidae (Fig. 1B; Fig. 2B). The coral

returned a late Pleistocene age of 283 ka (Table 2, SHP1_c), and the stromatolite a mid-Holocene age of 6 ka (SHP1_s). The reliability of the ages is questionable due to the high $\delta^{234}\text{U}$ values of 190‰ of the Upper Pleistocene coral, and the high ^{232}Th concentration suggesting potential detrital ^{230}Th contamination. However, despite these uncertainties in interpretation of the U-series ages, the stromatolite U-series age is clearly an upper limit and thus constrains the time of its growth to the recent Holocene. The age of the coral is constrained to MIS 5e or possibly the penultimate highstand, MIS 7).

4. Discussion

4.1. Chronological framework

As a part of a wider study of the Quaternary stratigraphy and sedimentology of Shark Bay, Logan et al. (1974) defined two transgressive marine successions, which he named the Dampier (older) and the Bibra (younger) Formations. Playford (1990) recognised that the Bibra Formation was likely formed during the peak of the last interglacial, MIS 5e. However, due to a lack of numerical ages, much of the emergent shallow marine deposits within Shark Bay were assigned to the middle Pleistocene Dampier Formation. U-series coral dates from sites across Shark Bay (Fig. 3) show that these emergent coral reef deposits were in fact laid down exclusively during MIS 5e, correlative with the Bibra Formation. The very-well-indurated nature of shallow marine (oolitic) and beach ridge deposits, outcropping intermittently along the coastal plain of Shark Bay

(Logan et al., 1974) provides evidence of active diagenetic processes associated with marine incursions during the Middle and Upper Pleistocene (MIS 9/11).

4.2. Timing of emplacement of major morphological features

The Zuytdorp sea cliffs of Edel Land, 150–250 m high, are by far the dominant feature along Shark Bay's oceanic coastline. Woomerange Hill, at 270 m is the highest point along this section of coast and is also the type section for the Tamala Limestone. Although not quantitatively dated it has been assigned middle to late Pleistocene age (Playford, 1990; Hearty and O'Leary, 2008). Based on the thickness and indurated nature of the sedimentary succession, it is likely that Edel Land and the Zuytdorp sea cliffs would have presented a distinct barrier feature during MIS 5e.

Dirk Hartog Island is an equally massive feature comprising Tamala eolianites and separated from Edel Land by the 3 km wide South Passage. Evidence of emergent MIS 5e fringing reefs along the southern tip of Dirk Hartog Island (Stirling, 1996) suggests that this seaway was active at that time. Like its modern analogue, currents through the passage would have been tidally driven, limiting the incursion of oceanic waters into Freycinet Reach. This would have left a northern entrance as the only viable route by which marine waters could penetrate deeply into the bay. Therefore knowledge of the timing of emplacement of Bernier and Dorre Islands are critical to the understanding of ocean dynamics in Shark Bay during MIS 5e.

Fig. 3. A) U-series coral ages for Shark Bay. The additional Shark Bay coral ages (in grey) were excerpted from Stirling et al. (1995) Fig. 4A. B) Initial ^{234}U values versus ^{230}Th age. Reliable U-series ages should fall within the $146.6 \pm 10\%$ initial $\delta^{234}\text{U}$ range. Unreliable ages with initial $\delta^{234}\text{U}$ range $>160\%$ were not included in Fig. 3A.

To assign an age to either Bernier or Dorre Islands is difficult as there has been little detailed study of the stratigraphy or lithology apart from what appears in the Geological Survey of Western Australia 1:250,000 geological series (SG49-4 and SG49-8, 1983) (Hocking et al., 1987). As yet no last interglacial marine deposits have been identified on either of these islands. This might suggest the islands were formed post MIS 5e or simply that emergent reef deposits have been completely eroded by modern marine processes.

The lack of field evidence therefore dictates that the existence of these islands during the last interglacial remains open to speculation. However, the current correlation of stratigraphic units on Bernier and Dorre Islands with those on Edel Land and Dirk Hartog Islands suggests that they were distinct barrier features during the last interglacial. If this is so how might oceanic water have penetrated deep within Shark Bays embayments during MIS 5e?

4.3. Coastal physiography

If the northern reaches of Shark Bay remained barred during MIS 5e, then an increase in oceanic circulation within the bay may have been facilitated by a modified coastal physiography. Where MIS 5e marine units and shoreline deposits do outcrop it is usually

proximal to the modern shoreline (Fig. 1B; Fig. 2A and C). This indicates that at least in these locations there was minimal dune migration or desert expansion during the intervening glacial, which allowed the modern shoreline to return to a similar position as the MIS 5e shoreline.

At the northern end of Tallifer Isthmus, an evaporite basin connects L'Haridon Bight and Henri Freycinet Harbour and may have been breached during the early Holocene. This was the site of a seaway between L'Haridon Bight and Freycinet Harbour during the last interglacial (Donald, 2003) and is potentially analogous to present day South Passage or Herald Loop. This narrow seaway would not have facilitated through-flow, as seawater exchange between the two marine basins would have been dominated by the flood and ebb tides as is evident in the present South Passage and Herald Loop (Burling et al., 2003). It would appear that the general coastal configuration of Shark Bay during MIS 5e is comparable to the modern shoreline and as such did not contribute to enhanced marine circulation during MIS 5e.

4.4. Holocene sea levels and the marine development of Shark Bay

A series of Holocene coquina beach ridges composed exclusively of the halotolerant mollusc species, *Fragum*

Fig. 4. Sea level curves for Shark Bay and respective timing of both coral and stromatolite development. MIS 5e curve was excerpted from Hearty et al. (in review) and the Holocene sea level curve was excerpted and modified from Fig. 5 in Collins et al. (2006).

erugatum are found along the southern margin of Hamelin Pool (Playford, 1990), with the oldest ridge returning an age of 5500 yr (Nott, 2006). This would suggest Hamelin Pool reached meta/hypersaline levels not long after the initial +2 m early-Holocene sea-level highstand event, which in Western Australia occurred around 7 ka (Collins et al., 2006; Eisenhauer et al., 1993) (Fig. 4). For such a rapid transition from oceanic to hypersaline conditions, it is likely a relict Pleistocene high (proto-Faure Sill), with its surface projections manifest in Faure and Pelican Islands, presented an initial barrier for seawater exchange between Hamelin Pool and Hopeless Reach. Tidal flow across this barrier facilitated ooid precipitation, with vertical bank accretion reducing sill depth to its current 2 m, while the basin itself has an average depth of 4 m. This bathymetric configuration, combined with a gradual late Holocene sea-level regression (Collins et al., 2006), further restricted oceanic circulation where by 1250 yr stromatolites had become firmly established (Chivas et al., 1990) and contemporary salinities now reach 60–70‰.

Reduced marine circulation is also aided by the lack of carbonate transport onshore, a consequence of shallow sand banks, extensive seagrass habitats and limited fetch, all of which reduce the ability of waves and currents to mobilise sediments. As a result, carbonate deposition has been confined exclusively to the bays and reaches, filling available accommodation space, reducing oceanic circulation and raising salinities. Given the present extent of the bank and shoal features and the fact that sea-level has only reached its present position within the last 7 ka (Collins et al., 2006), continual filling and further oceanic restriction within Shark Bay is expected.

Whilst Hamelin Pool might be considered the near end product of carbonate sedimentation, in a similar sense Freycinet Harbour represents an intermediate stage. Its northern Fork Flat Sill has an average depth of 5 m, the bay itself has an average depth of 10 m. This bathymetric configuration has resulted in a metahaline (46–48‰) environment. While Freycinet Harbour still supports extensive seagrass habitats and other carbonate producing communities, both coral and stromatolite communities are absent. We therefore observe that with a more porous sill and deeper basin, as in Freycinet Harbour, circulation is increased and the potential for hypersalinity is diminished. The question then arises, if carbonate production was and is such an active process during the most recent sea level highstand, and assuming similar processes operated during previous interglacial highstands, why then are habitats once occupied by a diverse coral fauna now the exclusive domain of stromatolites?

4.5. MIS 5e sea levels and the marine development of Shark Bay

The rapid onset of hypersaline conditions in Hamelin Pool during the Holocene is in marked contrast to the MIS 5e marine environment, which shows periods of coral growth between 129 and 124 ka and another around 122 ka (Fig. 3). The primary difference between these two highstand events is in their respective sea level histories. Sea levels during the early stages of MIS 5e were at least 3 m higher than they are today, as is evidenced from emergent last interglacial reef terraces in Shark Bay and other MIS 5e sites (McCulloch and Esat, 2000; Hearty and Neumann 2001). This would mean, assuming an average embayment depth of 10 m, that there was 30% more accommodation space available during MIS 5e, allowing for enhanced oceanic circulation (such as we observe in modern day Henri Freycinet Harbour), also increasing the time required to infill the embayment and hence ultimately restrict oceanic circulation.

Coral growth increased during the early and middle stages of MIS 5e and up to about 125 ka, before apparently abruptly halting at around 124 ka (Fig. 3). The cause of this reduction in coral reef development could be twofold. By 124 ka, carbonate sedimentation within the bays and reaches may have been sufficient to restrict marine circulation thereby increasing salinities, as is the current situation in Hamelin Pool. However, coral development along the oceanic sections of the bay also seems to show a similar pattern, suggesting that it was not controlled by local features and does not appear to be an artefact from a sampling bias. The other possibility is a regression in sea level caused by a brief but complete halt to coral development within the bay. Several sea-level curves for the last interglacial including those of Hearty and Neumann (2001) and Sherman et al. (1993), point to a brief regression in sea-level during mid 5e (Fig. 4). This could be correlated with the apparent age gap with the number of dated corals at 125 ka decreasing from six to nil at 124 ka.

Sea level is believed to have recovered from the mid-MIS 5e regression by 123 ka to an elevation of +3 to +4 m above current MSL (Hearty et al., 2007). This event saw a reestablishment of coral growth at sites deep within Shark Bay's embayments, including Pelican Island and Baba Head. The termination of MIS 5e was marked by a brief but rapid excursion to +6 to +9 m but to ongoing erosion evidence for this event has not yet been found at Shark Bay. At around 118 ka there was an apparent rapid descent to MIS 5d with the youngest Shark Bay coral being dated to 119 ka.

It would appear that the marine environments of Shark Bay have been strongly influenced by even relatively small changes in sea level. We observe that minor shifts in sea-level elevation can strongly affect the hydrodynamics of the bay, more so where embayments are deep and water depths shallow. Fluctuations in highstand sea levels can substantially influence salinity gradients, which in turn control the distribution type and extent of carbonate producing habitats.

5. Conclusions

U-series dating of emergent fossil reefs point to an extended period of coral reef development within Shark Bay during the peak of the last interglacial — MIS 5e. There is little evidence of fossil reef development during the Middle/Upper Pleistocene (MIS 9 to 11). This then places most of the fossil reefs previously assigned to the Dampier Formation (Middle Pleistocene) such as those at Tetrodon Loop and Monkey Mia into the Bibra Formation — MIS 5e. Therefore the occurrence of an emergent coral reef within Shark Bay can be positively correlated to MIS 5e and be used as a chronostratigraphic benchmark.

Coral reef development was widespread in MIS 5e Shark Bay compared to Modern Shark Bay. This can be attributed to higher sea levels and absence of major sill and bank structures that increase water depth, thereby enhancing marine circulation within the reaches and basins. Stromatolites are absent from the earlier geological record within Shark Bay; suggesting that the marine sedimentary processes that have operated over the present Holocene sea-level highstand were unique in filling available accommodation space and thus reducing oceanic circulation and causing hypersaline conditions within upper embayments of Shark Bay, whereas during MIS 5e the persistence of higher sea levels resulted in the embayments having more open marine conditions.

Acknowledgements

Fossil reefs within the Shark Bay World Heritage Area were sampled under a scientific permit issued by the Department of Conservation and Land Management, Western Australia. We would like to thank wildlife officers of the Denham CALM office for their logistical support in the collection of coral samples. Graham Mortimer and Les Kinsley provided technical support and a special thanks to Bob Burne who provided us with the Nilemah stromatolite sample. We thank Jody Webster for an earlier review of this manuscript and constructive comments and John Cann whose detailed

editorial contribution greatly improved the manuscript. Research funding was made available through an Australia Research Council Discovery Grant (ID: DP0209059) to M. McCulloch and P. Hearty, and grants from Kanagawa Museum, and an internal JCU merit research grant.

References

- Andres, M.S., Reid, R.P., 2006. Growth morphologies of modern marine stromatolites: a case study from Highborne Cay, Bahamas. *Sedimentary Geology* 185, 319–328.
- Bricker, O.P., 1971. Introduction: beachrock and intertidal cement. In: Bricker, O.P. (Ed.), *Carbonate Cements*. Johns Hopkins Press, Baltimore, MD, pp. 1–3.
- Burling, M.C., Ivey, G.N., Pattiaratchi, C.B., 1999. Convectively driven exchange in a shallow coastal embayment. *Continental Shelf Research* 19, 1599–1616.
- Burling, M.C., Pattiaratchi, C.B., Ivey, G.N., 2003. The tidal regime of Shark Bay, Western Australia. *Estuarine, Coastal and Shelf Science* 57, 725–735.
- Chen, J.H., Curran, H.A., White, B., Wasserburg, G.J., 1991. Precise chronology of the Last Interglacial period: $^{234}\text{U}/^{230}\text{Th}$ data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin* 103, 82–97.
- Cheng, H., Edwards, R.L., Hoff, J., Gallup, C.D., Richards, D.A., Asmerom, Y., 2000. The half-lives of uranium-234 and thorium-230. *Chemical Geology* 169, 17–33.
- Chivas, A.R., Torgersen, T., Polach, H.A., 1990. Growth rates and Holocene development of stromatolites from Shark Bay, Western Australia. *Australian Journal of Earth Sciences* 37, 113–121.
- Collins, L.B., Zhao, J.-X., Freeman, H., 2006. A high-precision record of mid–late Holocene sea-level events from emergent coral pavements in the Houtman Abrolhos Islands, southwest Australia. *Quaternary International* 145–146, 78–85.
- Donald, A., 2003. Marine and continental sediment flux in Shark Bay, Western Australia. B.Sc. Hons. Thesis, James Cook University, Townsville, Australia.
- Eisenhauer, A., Wasserburg, G.J., Chen, J.H., Bonani, G., Collins, L.B., 1993. Holocene sea-level determination relative to the Australian continent: U/Th (TIMS) and ^{14}C (AMS) dating of coral cores from the Abrolhos Islands. *Earth and Planetary Science Letters* 114, 529–547.
- Hatcher, B.G., 1991. Coral reefs in the Leeuwin Current — an ecological perspective. *Journal of the Royal Society of Western Australia* 74, 115–127.
- Hearty, P.J., Neumann, A.C., 2001. Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): evidence from The Bahama Islands. *Quaternary Science Reviews* 20, 1881–1895.
- Hearty, P.J., Neumann, A.C., Hollin, J.T., O'Leary, M.J., McCulloch, M.T., 2007. Global sea-level fluctuations during the last interglaciation (MIS 5e). *Quaternary Science Reviews* 26 (17–18), 2090–2112.
- Hearty, P.J., O'Leary, M.J., 2008. Carbonate eolianites, quartz sands, and Quaternary sea-level cycles, Western Australia: a chronostratigraphic approach. *Quaternary Geochronology* 3, 26–55.
- Hocking, R.M., Moors, H.T., Van De Graff, W.J.E., 1987. Geology of the Carnarvon Basin of Western Australia. Geological Survey of Western Australia Bulletin 133.
- Kendrick, G.A., Huisman, J.M., Walker, D.I., 1990. Benthic macroalgae of Shark Bay, Western Australia. *Botanica Marina* 33, 47–54.

- Logan, B.W., 1970. Carbonate sedimentation and environments, Shark Bay, Western Australia. *The American Association of Petroleum Geologists, Memoir* - 13, 223p.
- Logan, B.W., 1974. Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia. *The American Association of Petroleum Geologists, Memoir* - 22, 358p.
- Logan, B.W., Cebulski, D.E., 1970. Sedimentary environments of Shark Bay, Western Australia. *Memoir-The American Association of Petroleum Geologists* 13, 1–37.
- Logan, B.W., Read, J.R., Davies, G.R., 1974. History of carbonate sedimentation, Quaternary Epoch, Shark Bay, Western Australia. *Memoir-American Association of Petroleum Geologists* 13, 38–85.
- Marsh, L.M., 1990. Hermatypic corals of Shark Bay, Western Australia. In: Berry, P.F., Bradshaw, S.D., Wilson, B.R. (Eds.), *Research in Shark Bay. Report of the France-Australe Bicentenary Expedition Committee*. Western Australian Museum, Perth, pp. 107–114.
- McCulloch, M.T., Esat, T., 2000. The coral record of last interglacial sea levels and sea surface temperatures. *Chemical Geology* 169, 107–129.
- McCulloch, M.T., Mortimer, G., in press. The applications of the ^{238}U - ^{230}Th decay series to dating of fossil and modern corals using MC-ICPMS. *Australian Journal Of Earth Science*.
- Nott, J., 2006. Tropical cyclones and the evolution of the sedimentary coast of northern Australia. *Journal of Coastal Research* 22, 49–62.
- Playford, P.E., 1990. Geology of the Shark Bay area, Western Australia. In: Berry, P.F., Bradshaw, S.D., Wilson, B.R. (Eds.), *Research in Shark Bay. Report of the France-Australe Bicentenary Expedition Committee*. Western Australian Museum, Perth, pp. 13–31.
- Playford, P.E., Cockbain, A.E., Low, G.H., 1976. Geology of the Perth Basin, Western Australia. *Bulletin Geological Survey of Western Australia* 124, 298.
- Read, J.F., 1974. Calcrete deposits and Quaternary sediments, Edel Province, Shark Bay, Western Australia. *American Association of Petroleum Geologists, Memoirs* 22, 250–282.
- Robinson, L.F., Belshaw, N.S., Henderson, G.M., 2004. U and Th concentrations and isotope ratios in modern carbonates and waters from the Bahamas. *Geochimica et Cosmochimica Acta* 68, 1777–1789.
- Stirling, C.H., 1996. High-precision U-series dating of corals from Western Australia: implications for Last Interglacial sea levels. Ph.D. Thesis, Australian National University, Canberra, Australia.
- Stirling, C.H., Esat, T.M., McCulloch, M.T., Lambeck, K., 1995. High-precision U-series dating of corals from Western Australia and implications for the timing and duration of the Last Interglacial. *Earth and Planetary Science Letters* 135, 115–130.
- Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. *Earth and Planetary Science Letters* 160, 745–762.
- Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., Blake, S.G., Lee, D.C., Halliday, A.N., 2001. Orbital forcing of the marine isotope stage 9 interglacial. *Science* 291, 290–293.
- Walker, D.I., Woelkerling, Wm.J., 1988. Quantitative study of sediment contribution by epiphytic coralline red algae in seagrass meadows in Shark Bay, Western Australia. *Marine Ecology-Progress Series* 43, 71–77.

Further reading

- Teichert, C., 1950. Late Quaternary changes of sea-level at Rottnest Island, Western Australia. *Proceedings of the Royal Society of Victoria* 59, 63–79.