A high precision record of mid-late Holocene sea- level events from emergent coral pavements in the Houtman Abrolhos Islands, southwest Australia

Lindsay B. Collins[1], Jian-Xin Zhao[2] and Heather Freeman[1]

[1]Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth 6845, Australia, **L.Collins@curtin.edu.au**

[2] AQUIRE, Department of Earth Science, University of Queensland, Brisbane 4072, Australia, j.zhao@earthsciences.uq.edu.au

Author keywords: Holocene, sea-level change, U-series dating, coral pavements

A high precision record of mid-late Holocene sea- level events from emergent coral pavements in the Houtman Abrolhos Islands, southwest Australia

Lindsay B. Collins[1], Jian-Xin Zhao[2] and Heather Freeman[1]

Abstract

Early work on sea-levels in southwest Australia claimed to recognise a Holocene sea-level highstand which was not seen in better known sea-level records elsewhere at the time, and more recent work has confirmed that a mid Holocene highstand occurred about 6 ky ago. As new data on oscillating sea-levels from the region have recently been published, a high continuity, precisely dated and accurately surveyed record was obtained from emergent coral pavements in the leeward Houtman Abrolhos Islands (Serventy Island), a tectonically stable region from where good quality Holocene sea-level data have been previously obtained from corals. From the mid Holocene highstand close to 7 ky U/Th ago, sea-level declined linearly during the remainder of the Holocene as the carbonate platform prograded leewards. Hydro-isostatic cotrols are probably significant in the record.

1. Introduction

The discussion of evidence for smooth and oscillating sea-level events of the mid-late Holocene is continuing, with some recent work supporting the latter (eg. Angulo & Lessa, 1997; Camoin et al.2004; Zhao et al. 2002). At issue is the question of behaviour of sea- levels since the termination of the postglacial marine transgression around 6000 years ago, and the mechanisms of sea-level change (eg., glacio-eustatic vs. hydro-isostatic; see Lambeck & Nakada, 1990). The quality of sea-level data may vary with the use of sea-level indicators of differing sensitivity (shell material, corals or fixed biological indicators; see Baker & Haworth, 2000) and the precision of dating methods (14C vs. U-series TIMS). A different approach to sea-level variations has also been provided by Mörner (1992).

Some of the most detailed Holocene transgressive sea-level records have been obtained from coral reef systems in a variety of settings (Hopley, 1986), and the Houtman Abrolhos carbonate platforms, situated on Australia's western margin (Fig.1) provide one such example (Eisenhauer et al, 1993; Collins et al, 1993). Frequently, however, the precise details of the mid Holocene highstand, where it is recorded, and more particularly the shape of the subsequent sea-level regression of the past 6,000 years, are less well known. The lack of complete records has been attributed to glacio-isostatic adjustment, localised tectonics, insufficient dating and poor record continuity. The western Australian continent is relatively tectonically stable and consequently less affected by glacio-isostatic adjustment due to its 'far-field' location, and thus eustatic changes should be well reflected in the data.

The Houtman Abrolhos are a chain of shelf margin coral reefs located 60 – 70 km offshore from Geraldton and extend for 172 km parallel to the Western Australia coast. The Abrolhos contains ~120 small, low-lying islands and reefs grouped together into 3 main platforms; Wallabi Reef Complex, Easter Reef Complex and the Pelsaert Reef Complex (Fig. 1). They are each composed of a windward reef, central platform and a 40 m thick, Holocene leeward reef. The leeward islands consist of emergent coral reef, overlain by cemented pavements which are 0.4 to 1.6 m above MSL. The Houtman Abrolhos have yielded a relatively detailed sea-level record, particularly until the mid Holocene highstand, which is recorded by the emergent, cemented coral shingle pavement in many of the leeward islands of the three Abrolhos platforms. Similar pavements are forming today in peritidal conditions, and these provide a means of estimating sealevel. Whilst the fossil pavements have been dated at a few locations (see Collins et al, 1993) and have yielded ages around 5-6 ky, detailed surveying and dating were lacking in earlier studies.

Emerged conglomerate platforms (variously termed “brecciated coral rock”or “reef-conglomerate”) were first described by Darwin (1842) from the Cocos Keeling Islands, and similar lithified deposits at or above high tide have also been described from the Maldives (Gardiner, 1936) and Pacific atolls (Montaggioni & Pirazzoli, 1984). In discussing modes of origin for platforms in the Chagos Archipelago, Eisenhauer et al, 1999, p29) noted that reef platforms with gently falling slopes form during periods of linearly falling sea level. In the Houtman Abrolhos Islands, the emergent platforms capping the leeward reefs slope distinctly towards the leeward platform margin (see Collins et al, 1997).

The purpose of this study was to determine the elevation and age structure of the emergent reef pavements in an attempt to develop a detailed chronology of mid to late Holocene sea-level events preserved in the leeward Abrolhos islands. Based on mapping, U-series dating and determining the elevation of the ‘stillstand’ coral pavements, and comparison with the age structure of the underlying reef (Eisenhauer et al, 1993; Collins et al, 1993), we present here a far more detailed and reliable sea-level curve for the mid-late Holocene than previously available. The implications of past sea-level changes for coral reef island evolution and coastal morphology are also important in natural resource planning and management for this area of high ecological, economic and tourism value.

2. Methods

A survey of leeward island sites with emergent coral pavements likely to contain a relatively continuous and accessible record of sea-level events resulted in the selection of Serventy Island in the Easter Group for detailed study. Fieldwork in a 10-day period consisted of a series of surveyed traverses across the island.

Topographic profiles were obtained to aid in the construction of models for island evolution, storm ridge accretion and sea-level change. Sampling of emergent coral pavements was carried out for dating mid-late Holocene sea level history. The topological survey was accomplished using a Wild T1 Micrometer Theodolite, a Geodimeter connected to an external 12V battery, a single prism reflector with bubble staff, and a tripod. The Geodimeter was mounted on the theodolite telescope to measure horizontal and vertical distances. Under clear atmospheric conditions, the Geodimeter accuracy is ± 5mm/km, or 1:20,000, so the maximum distance recorded (173m) had an error of ± 8.6mm. Traverses commenced and finished at tidal stations where 'zero' elevation was assigned to MSL, established by placing tide poles in the substrate and recording the elevation at high tide to the top of a mapped pavement, to ± 0.05m. High tide was corrected to mean sea level using a cosine-curve tide prediction graph, from the Australian National Tide Tables (2002). Tidal range at the Abrolhos is 1 metre.

Samples were collected from coral pavement from exposed areas around the island. Head corals were taken from the top of each unit and their GPS location and elevation with respect to present sea-level recorded.

Coral samples (of *Acropora* spp) were selected for U-series dating by thermal ionisation mass spectrometry (TIMS). Samples were cleaned by removing algal encrustation and borings, then cut into 5 – 6 g blocks. Half of the sample was used for X-Ray diffraction (XRD) analysis and half was dated by AQUIRE at the University of Queensland by U-series TIMS dating. Mineralogical screening by XRD was used to reject aragonite coral samples with over 2% calcite. The screened coral samples of 1-2 g were ultrasonically cleaned and then dated using high precision mass-spectrometric methods. These results are presented in Table 1.

3. Results

3.1 Serventy Island Morphology. Located northeast of the Easter Group central platform, at 28°41’00’’ S, 113°49’53’’ E, Serventy Island is arcuate in shape, curving towards the central platform, and approximately 13 km^2 in area. The island represents the emergent part of the Holocene leeward reef crest and associated blue-hole complex. Of the four island types at the Abrolhos, Serventy Island is a composite island, the most common type (Fig 2; see Collins et al, 1997). Composite islands consist of 1-3 m high, leewards- prograding storm ridges of unconsolidated coral rubble. Cemented coral framestone ‘pavement’, usually 0.5-1 m thick, underlies the ridges, and is commonly exposed on the lagoon side of the island and edges of internal sinkholes. Here the pavement unit lies in the intertidal/supratidal zone and usually has a well developed intertidal notch. The pavement is emergent by up to 1.6 m on the westerly, lagoon side of the island, but typically slopes eastward towards the ocean side or platform margin side of the island, where it is not exposed beneath the overlying coral rubble storm ridges (Fig 3). Below the pavement the Holocene reef is 40 m thick; shallow subtidal reefs surround the island on the westerly, lagoon side and the leeward reef crest slopes away sharply adjacent to the east coast at the leeward platform margin. Based on the falling elevations of both the pavement and the overlying storm ridges as the leeward platform margin is approached, and the patterns of storm ridge accretion, it is clear that the island grew, initially from two separate nuclei, by leeward progradation as successive storm ridges were added. The ridges are grouped in five recognisable packages or accretion cycles (Fig 3). The overall decreasing elevation of both storm ridges and pavement in the direction of younging further suggests that sea-level was generally decreasing throughout the period of island growth and deposition.

3.2 Pavement elevations and ages. Emergent pavements are composed of well lithified, bedded coral rudstone which consists of gravel size coral plates and sticks in variable proportions. Sand size carbonate sediment of lagoonal aspect fills most interstices in the rudstone frame. Coralline algae frequently encrust coral plates and rods throughout pavements, attesting to cementation within a high energy, shallow subtidal environment. The pavements directly overlie emergent Holocene coral reef framestone which, near the contact, has a veneer of encrusting coralline algae as the last expression of vertical reef growth. Contemporary equivalents of the fossil pavements are forming today in reef flat environments as subtidal sheets of coral rubble on the relatively protected, seaward side of most leeward islands, including Serventy Island. These deposits are just exposed during extreme low tides, and given a tidal range of 1 m, modern pavement surfaces have an estimated elevation of 0.4 m below MSL. A similar estimate has been made for the fossil pavements which are laterally continuous with the contemporary pavements.

Emergent coral rudstone pavement heights were determined from field traverses and tidal data with respect to MSL (Fig. 3). Nine pavement elevations were recorded from Serventy Island. Dated pavement samples range from 6832 to 1058 U/Th years (see Table 1) and are summarised in Table 2. Pavement elevations fell within the range 0.46 to 1.62 m above MSL, with the lowest elevation coinciding with the youngest age (HS4; 1058 y) and the highest elevation coinciding with the oldest pavement age obtained (HST5; 6832 y). The oldest ages and highest elevations are found in the oldest of the four storm ridge accretion units which comprise the island,

and the ages and elevations of other samples progressively decrease through the remaining accretion units , from oldest to youngest (see Table 2).

The mid-late Holocene sea-level history curve generated from the pavement age and elevation data (see Fig 4) indicates that the mid Holocene highstand reached an elevation of at least 1.62 m and an estimated 2.05 m (based on the actual pavement elevation and its estimated associated sea-level, respectively) above MSL at 6832 U/Th y ago. Following the highstand the data suggest that subsequent sea-level declined in a relatively uniform way until 1058 U/Th y, indicated by the youngest and lowest pavement sampled, then continued to decline to present MSL. The record obtained is of high precision, especially for sea-level records of its type, with an error in measured heights of only ± 0.05 m and a dating error of ± 34 y or 0.5%.

The most significant excursion from the linear trend in the data is represented by the elevation of sample HST4, which is significantly lower than other corresponding pavement samples of a similar age (HST5, HST7 and HST8). This sample was sourced from the edge of a mangrove-lined depression, thought to be a relict blue hole. Both subsidence of the pavement and erosional loss of its uppermost surface (as distinct from the 8 other in-place pavement surfaces sampled) is thought to have decreased the elevation of this sample by up to 0.5 m, rendering its recorded height unreliable. Further, the three other samples (HST5, HST7 and HST8) of similar age to HST4 have elevations which lie within 0.2 m of each other, providing close agreement in the data. Samples HST1 and HS3 are also 0.2 m below the linear decline trend; of these HST1 is of similar age to HST2, which is 0.25 m higher, and on-trend. It remains, however, arguable that HS3 represents a temporary reduction of sea-level by 0.2 m below the linear regression trend, at 3226 y ago. Also, there has been an increased rate of sea-level fall between 1058 y ago (HS4) and attainment of present MSL (see Fig 4). In summary, and given the exceptions described, the overall trend in the data supports a smooth rather than oscillating behaviour for sea-level at the Abrolhos since the 2 m highstand recorded at 6832 y ago.

3.3 Comparison with previous Abrolhos sea-level data

Previous studies of coral reef growth history at the Abrolhos have focused on coring and U-series dating of both the Last Interglacial reefs (Zhu et al, 1993) and Holocene reefs (Eisenhauer et al, 1993; Collins et al, 1993). The leeward islands of the Easter Group were cored at Morley and Suomi Islands, to the south of Serventy Island but in the same island chain, with a similar stratigraphy and position relative to the leeward reef crest. Of these, Morley Island most closely resembles a "keep-up reef" (see Collins et al, 1993; Eisenhauer et al, 1993). The total Holocene reef thickness is 40 m in the leeward reefs (Collins et al, 1996) so reef growth was initiated around 11.3 ky ago, using the calculated growth rate for the lower part of the Morley core.

By combining the core data with the pavement ages determined in this study, and some pavement ages determined previously, a composite sea-level curve has been generated (Fig 5). The U-series ages of the Holocene highstand and subsequent linear decline fit well with the coral reef core ages, and the curve shows the transgression, with two gradients, decreasing toward the stillstand at close to 7000 years ago, followed by the subsequent decline to the present.

A comparison between the ages of the Morley core and the relatively younger Suomi core (Eisenhauer et al, 1993) indicates that growth of the leeward reef was diachronous, and it follows that the islands (including their coral pavements and overlying storm ridges), which are the emergent portions of the system, will also be diachronous. Evidence that the leeward reef has prograded in a leeward (eastward) direction during its growth through time comes from the span of coral core ages obtained, distinct patterns of leeward island growth by successive storm ridge accretion, (as found at Morley, Suomi, Serventy and other leeward islands) and the 7000 year history of growth of the leeward-sloping pavements dated from Serventy Island.

3.4 Comparison with Australian sea-level data

The western Australian continental margin is tectonically relatively stable and is less affected by glacio-isostatic adjustment, due to its 'far-field' location, however the amplitudes of Holocene highstands along the Australian coast vary between 1 and 2.5 m above present sea-level (Table 3). In southwest Australia the more recent work has confirmed the existence of a highstand centred on 6 ky BP, most probably a reflection of hydro-isostatic processes, but the question of a possible tectonic signal has remained to be resolved (see review in Wyrwoll et al, 1995). The mid Holocene highstand elevations reported from both the east and west coasts of Australia are from data based on various sea-level indicators, such as corals, shells and fixed biological indicators (FBI) including tubeworms, barnacles and oysters. Coral data represent a minimum sea-level, whilst the FBI's exist in the inter-tidal zones, just above or below mean sea level. The Holocene highstand (+2 m at 6832 y U/Th) reported here is one of few reported coral pavement ages, and falls at the higher and oldest end of the envelope of highstands from the sources summarised in Table 3.

4. Discussion and Conclusions

Some of the most quoted early Australian data were those of Fairbridge (1961) from southwest Australia, where multiple, oscillating highstands were reported from a tectonically stable setting. However, there was no similar recognition of a Holocene highstand in eastern Australian work until the possibility that the data envelope in the sea-level curves allowed a relative sea-level 1 m higher than present was recognised (Thom & Roy, 1983). Both the eastern Australian data and hydro-isostatic rebound models suggested a stable to smoothly falling Late Holocene sea-level curve (Lambeck, 1993).

More recently, reports from the Australian region (Baker & Haworth, 2000, Baker et al, 2001) and southern Brazil (Angulo et al, 1999) have used fixed biological indicators to document Holocene evidence for complex, oscillating sea-levels following highstand conditions, questioning the hypothesis of a slow but smooth Late Holocene sea-level fall, and this work is continuing.

Data obtained in this study are from a region where high quality sea-level information has been previously obtained from coral reefs in a tectonically stable, “far-field” setting. The use of accurately surveyed sample sites (elevations to ± 0.05 m) and high precision U-series TIMS dating, collected from a single, small island location where the stratigraphy and sea-level history are relatively well known is an approach designed to minimise noise in the sea-level data. The data obtained indicate a smooth decline of sea-level since the 2 m highstand at 6832 y U/Th ago, but with higher precision and greater reliability than obtained in previous Abrolhos studies. In addition, hydro-isostatic adjustment is likely to be reflected in the data, which shows a general correspondence with the Geraldton numerical model curve (for the mainland 70 km due east of the Abrolhos) of Lambeck & Nakada (1990).

One of the possible sources for variability in the Abrolhos sea-level data is the Leeuwin Current, an ocean current of warm, low-salinity water, which flows poleward from northwest Australia along the shelf break near the Abrolhos Islands. The current results from development of a large along-shore pressure gradient between warm equatorial waters and cool Southern Ocean waters, and the meridional gradient induces a net eastwards geostrophic flow from the Indian Ocean towards Australia, which is then deflected southwards by the continent, and fluctuations in the current have the potential to influence sea-level at the Abrolhos (Pearce, 1991).

Rottnest Island, some 500 km to the south of the Abrolhos, also lies in the path of the Leeuwin Current, and here a rapid sea-level fall of 1 m occurred, perhaps related to Leeuwin Current fluctuations (Playford, 1988, Baker et al, 2001). The rapid fall at 3500 cal. y marked a cooling event which extended for 900 y to 2600 cal. y, based on evidence from fixed biological indicator successions and the incidence of the temperate mollusc *Katelysia*, which today occurs 300 km to the south (Playford, 1988, Baker et al, 2001). In comparison, the Abrolhos record has a 20 cm departure from a linear decline (see Fig 4; HS3) at 3225 y U/Th, and this decreased sea-level appears to be weakly registered in the data, albeit as a small inflection in the curve. However, this correlation would require further substantiation from within more Abrolhos data to be sustained. Whilst it is known that Leeuwin Current fluctuations have occurred, for example between the Holocene and Last Interglacial (Zhu et al, 1993) the Holocene was a period where Abrolhos reefs, sustained by the Leeuwin Current, had growth rates as fast as those of tropical reefs, and there are no other recorded fluctuations.

In addition to their use as sea-level indicators, coral pavements in the world's reefs offer considerable potential as palaeoclimate indicators, provided precise chronological data are available. In a study of the Chagos Islands, coral pavement age distribution was used to indicate periods of coral platform growth, and to provide correlations with other climate cycles indicated by data from ice cores, alpine glacier expansions and pollen records (Eisenhauer et al, 1999). In the Abrolhos there are over 100 islands, and many of these contain coral pavements which are overlain by storm ridge sequences composed of coral rubble; work is continuing so that sea-level analysis can be linked to events of past climates recorded in the storm ridges.

5. Acknowledgements

This study was supported by research grants at Curtin University of Technology and the University of Queensland. Logistic support for fieldwork at the Abrolhos Islands was provided by Fisheries WA, who are thanked for their interest and support. The first author also thanks colleagues in IGCP 464 for advice and assistance.

6. References

Angulo, R.J., and Lessa, G.C., (1997). The Brazilian sea-level curves: a critical review with emphasis on the curves from Paranagua and Cananeia regions. Marine Geology 140:141-166.

Angulo,R .J., Giannini, P.F.C., Suguio, K., and Pessenda, L.C.R., (1999). Relative sea-level changes in the last 5500 years in southern Brazil (Laguna-Imbituba region, Santa Catarina State) based on vermetid 14C ages, Marine Geology 159:323-339.

Baker, R.G.V., & Haworth, R.J., (2000). Smooth or oscillating late Holocene sea-level curve? Evidence from cross-regional statistical regressions of fixed biological indicators. Marine Geology 163:367-386

.

Baker, R. G. V., R. J. Haworth, and Flood, P.G.,(2001). Inter-tidal fixed indicators of former Holocene sea levels in Australia: a summary of sites and a review of methods and models. Quaternary International **83-85**: 257-273.

Camoin, G.F., Montaggioni, L.F., and Braithwaite, C.J.R., (2004). Late Glacial to post glacial sea levels in the western Indian Ocean. Marine Geology 206:119-146.

Collins, L.B., Zhu, Z.R., Wyrwoll, K-H, Hatcher, B.G., and Playford, P.E. (1993). Holocene growth of a reef complex on a cool-water carbonate margin: Easter Group of the Houtman Abrolhos, Eastern Indian Ocean. Marine Geology 115:29-46.

Collins, L. B., Z. R. Zhu, and Wyrwoll, K-H., (1996). The structure of the Easter Platform, Houtman Abrolhos Reefs: Pleistocene foundations and Holocene reef growth. Marine Geology **135**: 1-13.

Collins, L. B., Z. R. Zhu, et al. (1997). Geology of the Houtman Abrolhos Islands. Geology and Hydrogeology of Carbonate Islands. Developments in Sedimentology. H. L. Vacher and T. Quinn. U.S.A, Elsevier. **54:** 811-813.

Darwin, C., (1842). The Structure and Distribution of Coral Reefs, South Elder, London, pp 1-214.

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 14C (AMS) dating of coral cores from the Abrolhos Islands, Earth and Planetary Science Letters 114: 529-547.

Eisenhauer, A., Heiss, G.A., Sheppard, C., and Dullo, W.C. (1999). Reef and island formation and Late Holocene sea-level changes in the Chagos islands. Ecology of the Chagos Arhipelago (ed. C.R. Sheppard & M.R.D. Seaward).

Fairbridge, R.F.,(1961) Eustatic changes in sea level.. In: Ahrens L.H., Press, F., Rankama,K., and Runcorn, S.K.(eds). Physics and Chemistry of the Earth (4). London: Pergamon pp. 99-185.

Gardiner, J.S., (1936). The reefs of the western Indian Ocean, 1, Chagos archipelago, H, The Mascarene region. Proceedings of the Linnean Society of London (2) 19:393-436.

Hopley, D., (1986). Corals and reefs as indicators of palaeo-sea levels. In: van de Plassche, O. (Ed.), Sea Level Research. Geo Books, Norwich, pp. 195-228.

Lambeck, K., (1993). Glacial rebound and sea-level change: an example of a relationship between mantle and surface processes. Tectonophysics 223: 15-37.

Lambeck, K. and Nakada, M., (1990). Late Pleistocene and Holocene sea-level change along the Australian coast. Palaeogeogr., Palaeoclimatol., Palaeoecol. 89: 143-176.

Larcombe, P. and Carter, R.M., (1998). Holocene bay sedimentation and sea levels,Magnetic Island. Short geological field trips in the Townsville –Charters Towers region. D.P.Johnson and R.A. Henderson, Geological Society of Australia:72-79.

Montaggioni, L.F., Pirazzoli, P.A., 1984. The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indicators of recent relative sea-level changes. Coral Reefs 3:29-42.

Mörner, N.A., (1992). Sea-level changes and earth's rate of rotation. Journal of Coastal Research 84: 966-871.

Pearce, A.F., (1991). Eastern Boundary currents of the southern hemisphere. Journal of the Royal Society of Western Australia, 74:35-46.

Playford, P.E., (1988). Guidebook to the geology of Rottnest Island. Geological Society of Western Australia, Western Australian Division. Excursion Guidebook No.2.

Searle, D.J. and Woods, D.P., (1986). Detailed documentation of a Holocene sea level record in the Perth Region, southern Western Australia. Quaternary Research 26:299-308.

Thom, B.G, and Roy,P. (1983). Sea-level change in new South Wales over the past 15,000 years. In Hopley, D.(Ed); Australian sea levels in the last 15,000 years; a Review. James Cook University, Townsville, pp. 64-84.

.

Wyrwoll, K.-H., Zhu, Z.R., Kendrick, G., Collins, L.B., & Eisenhauer, A., (1995). Holocene sea-level events in Western Australia: Revisiting old questions. Journal of Coastal Research Special Issue No. 17:P.321-326.

Zhao, J.X., and Yu, K.F., (2002). Timing of Holocene sea-level highstands by mass spectrometry U-series ages of coral reef from Leizhou Peninsula, South China Sea: Chinese Science Bulletin, v.47, p.348.352.

Zhu, Z.R., Wyrwoll, K-H., & Collins, L.B., (1993). High precision U-series dating of Last Interglacial events by mass spectrometry: Houtman Abrolhos Islands, Western Australia. Earth and Planetary Science Letters 118: 281-293.

Tables

Table 1. U-Th age and isotopic data.

Table 2. Summary of dated pavement samples, ages and elevations. For sample locations see Fig 3.

Table 3. Mid Holocene highstands from Western and Eastern Australia, (Queensland and New South Wales). Relative highstands are shown by elevation (m above MSL) and time (in U/Th years B.P.).

Figures

Figure 1 – Location of the Houtman Abrolhos carbonate platforms, Easter Group, and Serventy Island.

Figure 2- Morphostratigraphy of a composite island, from Abrolhos leeward islands, showing bedded coral rudstone pavement and overlying storm ridges (from Collins et al, 1997).

Figure 3- Map of Serventy Island showing sample locations and elevations, and also storm ridge accretion units (1-5).

Figure 4- Predicted sea-level data from Serventy Island, based on U-series dates of surveyed pavement samples. Actual sea-level is estimated to lie 0.4 m above measured pavement elevations.

Figure 5- Composite Holocene sea-level curve, based on Morley core (Eisenhauer et al, 1993; Collins et al. 1993) and pavement data from Serventy Island from this study.

Table 1.

Table 1. U-Th isotopic and age data. Ratios in parentheses are activity ratios calculated from the atomic ratios. Errors are at 2σ level for the least significant digits. The ages (in years before 2003) are calculated by Isoplot/EX program using half-lives from 230Th and 234U of 75,380 and 244,600 years, respectively. The corrected 230Th ages and initial (234U/238U) ratios include a negligible to small correction for initial/detrital U and Th using average crustal 232Th/238U atomic ratio of 3.8±1.9 (230Th, 234U

Sample Name	U (ppm)	±2σ	^{232}Th (ppb)	$(^{230}Th/^{232}Th)$	$(^{234}U/^{238}U)$	±2σ	$(^{230}Th/^{238}U)$	±2σ	Uncorr. ^{230}Th Age (yr)	±2σ	corr. ^{230}Th Age (yr)	±2σ	corr. Initial $(^{234}U/^{238}U)$	±2σ	$\delta^{234}U(T)$	±2σ
HMT1-PAVE	3.5168	0.0033	2.67	244	1.1449	0.0018	0.06085	0.00023	5933	25	5913	27	1.1474	0.0018	147.4	1.8
HS3-PAVE	3.8805	0.0029	0.83	478	1.1498	0.0016	0.03368	0.00057	3231	56	3226	56	1.1511	0.0016	151.1	1.6
HS4-PAVE	3.7940	0.0029	0.52	247	1.1498	0.0018	0.01117	0.00010	1061	10	1058	10	1.1503	0.0018	150.3	1.8
HSP3-PAVE	3.7742	0.0030	1.41	199	1.1490	0.0016	0.02452	0.00012	2344	12	2335	13	1.1500	0.0016	150.0	1.6
HST1-PAVE	4.1419	0.0035	0.99	505	1.1519	0.0025	0.03997	0.00033	3838	33	3831	33	1.1536	0.0026	153.6	2.6
HST2-PAVE	3.3552	0.0055	1.14	358	1.1479	0.0034	0.04022	0.00026	3876	28	3867	28	1.1495	0.0034	149.5	3.4
HST4-PAVE	3.7330	0.0029	1.73	427	1.1483	0.0017	0.06506	0.00019	6335	22	6323	23	1.1510	0.0018	151.0	1.8
HST5-PAVE	3.6684	0.0053	0.33	2363	1.1345	0.0029	0.06918	0.00028	6834	34	6832	34	1.1371	0.0030	137.1	3.0
HST7-PAVE	3.5056	0.0034	1.32	485	1.1482	0.0027	0.06004	0.00026	5834	29	5825	30	1.1507	0.0027	150.7	2.7
HST8-PAVE	3.6237	0.0051	0.72	1085	1.1522	0.0025	0.07116	0.00029	6924	33	6919	33	1.1552	0.0026	155.2	2.6

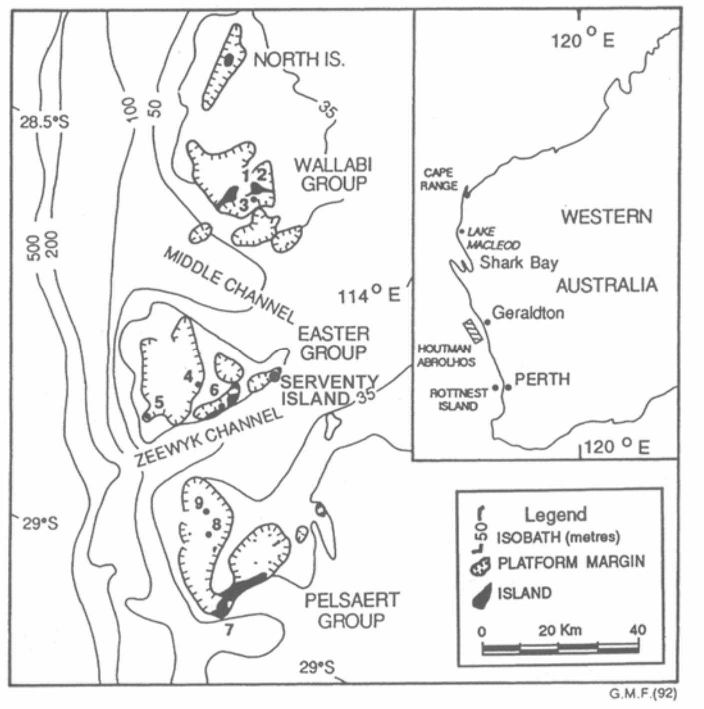
Table 2. . Mid Holocene highstands from Western and Eastern Australia, (Queensland and New South Wales). Relative highstands are shown by elevation (m above MSL) and time (in U/Th years B.P.).

Sample	**Age (U/Th y BP)**	**Elevation (m above MSL)**	**Storm Ridge unit**	**GPS Position Lat 28 Long113**
HST5	6832 ± 34	1.62 ± 0.05	1	40.865 49.804
HST7	5825 ± 30	1.46 ± 0.05	1	40.871 49.808
HST8	6919 ± 33	1.42 ± 0.05	1	40.70 49.80
HST4	6323 ± 23	0.8 ± 0.05	1	40.885 49.859
HST2	3867 ± 28	1.03 ± 0.05	2	41.082 49.936
HST1	3831 ± 33	0.78 ± 0.05	3	41.142 49.928
HST3	2335 ± 13	0.73 ± 0.05	3	41.04 49.91
HS3	3226 ± 56	0.67 ± 0.05	3	41.152 49.91
HS4	1058 ± 10	0.46 ± 0.05	4	41.255 49.819

Table 3. Mid Holocene highstands from Western and Eastern Australia, (Queensland and New South Wales). Relative highstands are shown by elevation (m above MSL) and time (in years B.P.).

Location	Highstand (y B.P.)	Description	Reference
Morley Is., Abrolhos,WA	0.6 m at 6320 U/Th (elevation at 0.2m)	Coral core.	Eisenhauer et al., 1993
Pearse Lake, Rottnest Is.,WA.	2.1 m at 5890 y cal.	Serpulid Tubeworm, under wavecut platform	Playford, 1988
Rockingham Beach, WA.	2.5 m at 6400 y cal.	Sea level curve from shell material	Searle and Woods, 1986
Magnetic Island, Qld	1.65 ± 0.05 m at 6050 y cal.	*S. cucculata* oyster, sheltered cave	Larcombe and Carter, 1998
Port Hacking, central NSW	1.0 ± 0.2 m at 5080 y cal.	Barnacle entombed by tubeworm at bedrock floor	Baker et al., 2001
Vaucluse, central NSW	1.4 ± 0.5 m at 5500 y cal.	Surf barnacle on bedrock, shelterd site	Baker et al., 2001
Dark beach, southern NSW	1.3 ± 0.25 m at 4990 y cal.	Tubeworm within barnacle, sheltered cove	Baker et al., 2001

Figure 1.



NORTH IS.
28.5°S
100
50
35
WALLABI GROUP
500
200
MIDDLE CHANNEL
114° E
EASTER GROUP
SERVENTY ISLAND
35
ZEEWYK CHANNEL
29°S
PELSAERT GROUP
29°S
120° E
CAPE RANGE
LAKE MACLEOD
Shark Bay
WESTERN AUSTRALIA
Geraldton
HOUTMAN ABROLHOS
PERTH
ROTTNEST ISLAND
120° E
Legend
ISOBATH (metres)
PLATFORM MARGIN
ISLAND
0
20 Km
40
G.M.F.(92)

Figure 2

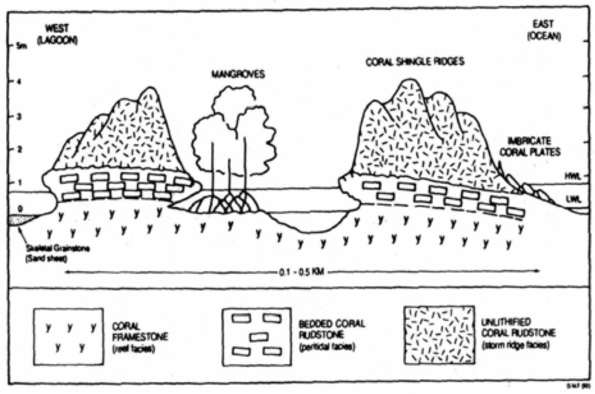
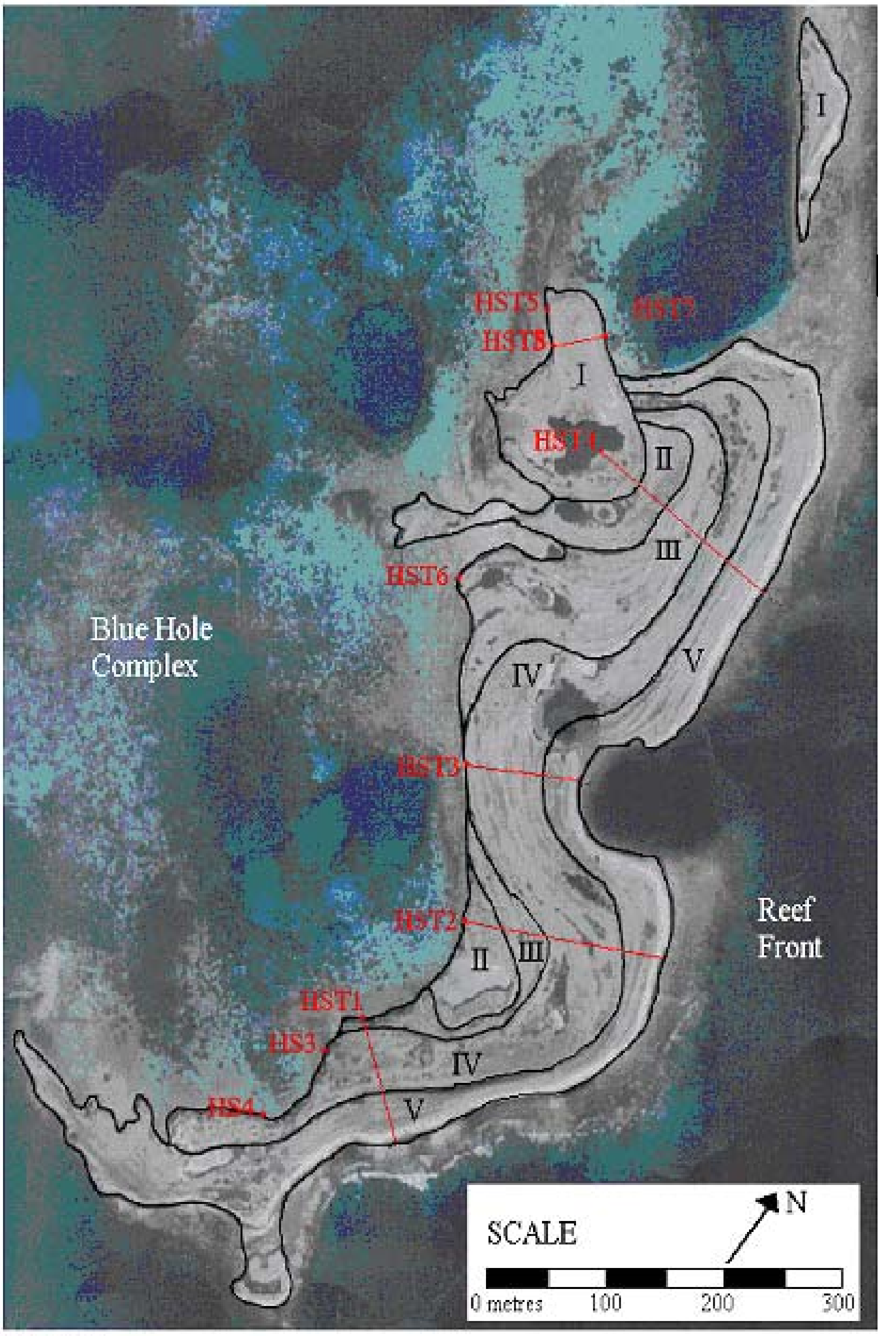

WEST
(LAGOON)
EAST
(OCEAN)
5m
4
3
2
1
0
MANGROVES
CORAL SHINGLE RIDGES
IMBRICATE
CORAL PLATES
HWL
LWL
Skeletal Grainstone
(Sand sheet)
0.1 - 0.5 KM
CORAL
FRAMESTONE
(reef facies)
BEDDED CORAL
RUDSTONE
(peritidal facies)
UNLITHIFIED
CORAL RUDSTONE
(storm ridge facies)

Figure 3



Legend

I Storm ridge units I to V, numbered oldest to youngest

Sampling Traverses

Tidal observation points

• HST6 Pavement Sample Site

Figure 4

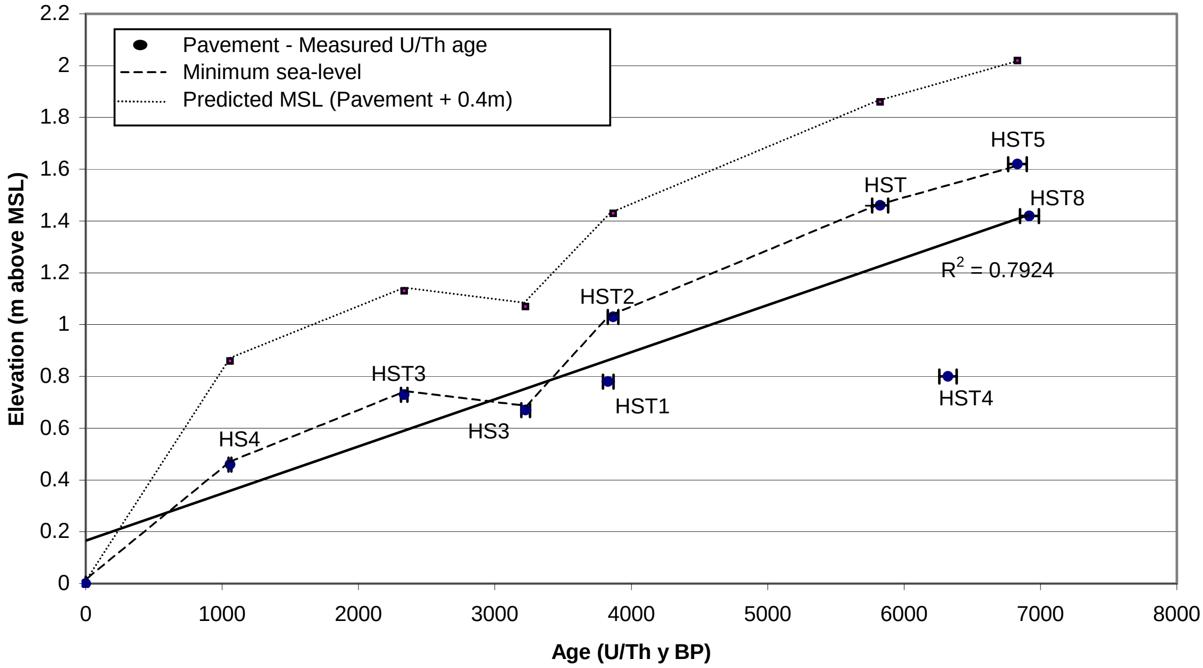
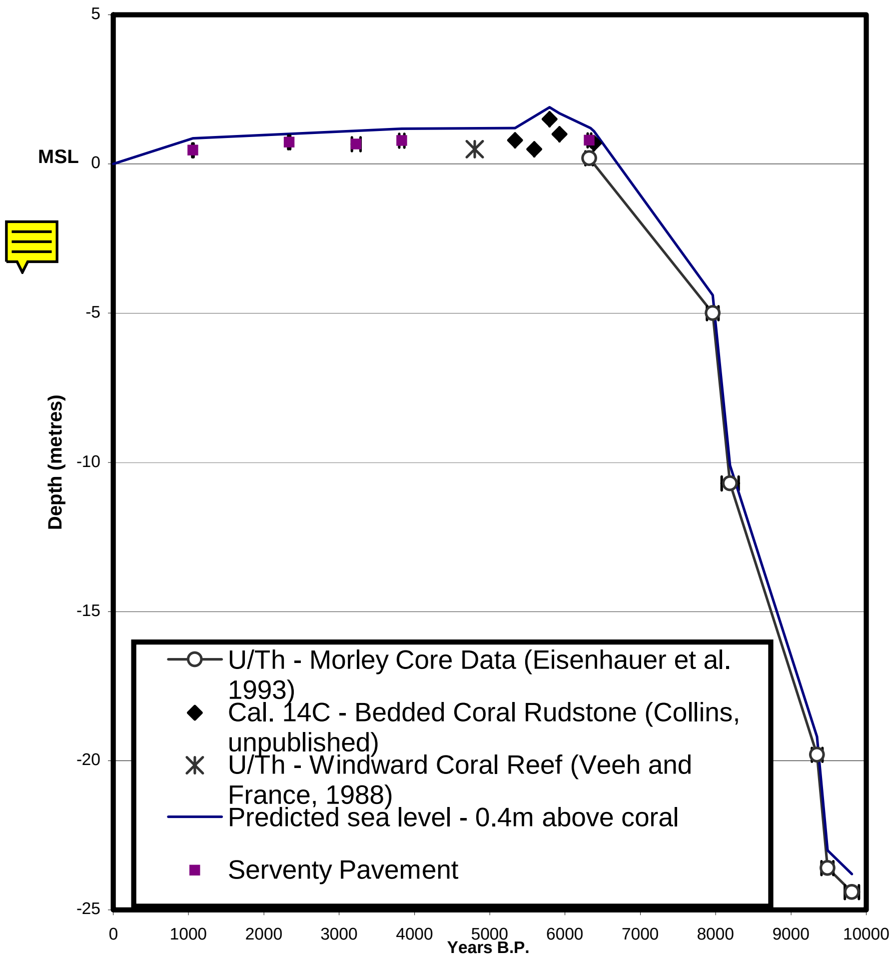

Pavement - Measured U/Th age
Minimum sea-level
Predicted MSL (Pavement + 0.4m)
Elevation (m above MSL)
Age (U/Th y BP)
HS4
HST3
HS3
HST2
HST1
HST
HST5
HST8
HST4
R2 = 0.7924
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1000
2000
3000
4000
5000
6000
7000
8000

Figure 5


5
MSL 0
-5
-10
-15
-20
-25
Depth (metres)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Years B.P.
U/Th - Morley Core Data (Eisenhauer et al. 1993)
Cal. 14C - Bedded Coral Rudstone (Collins, unpublished)
U/Th - Windward Coral Reef (Veeh and France, 1988)
Predicted sea level - 0.4m above coral
Serventy Pavement