Ningaloo Marine Park – Reef Morphology and Growth History

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WAMSI Project 3.4.1

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WAMSI 3.4.1 Characterisation of Geomorphology and Growth History

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1. Executive Summary

Little research has been done on the morphology and growth history of Ningaloo Reef to date, but it is considered that an understanding of underlying geomorphological factors will have a direct bearing on the nature and distribution of substrates and communities, both within the reef system and on the adjacent shelf.

Preliminary growth history studies have revealed two stages of reef growth; a “Tantabiddi phase” during which a large fringing reef grew in an active stage of Leeuwin Current flow (ca 125 ky U/Th ago), and a “Holocene phase” during which today’s reef recolonised the earlier reef (active reef growth during the last 7ky U/Th; Collins et al, 2003). During habitat mapping of Sanctuary Zones in 2004 (Cassata & Collins, 2008) it was recognised that much of the lagoon substrate and geomorphology is inherited from the earlier stage of reef growth.

This research mapped this relationship through extended habitat mapping (an adjunct to biodiversity assessment in Project 3.1), regional geomorphic mapping and selected shallow coring and dating in the lagoon and near the reef crest. This will facilitate predictions of reef response to sea-level change which is linked to potential changes in energy flux across the lagoon and at the shoreline, which is aligned to the climate change assessments.

Within budgetary limitations the growth history objective of WAMSI Project 3.4 used shallow coring of the western reef flat to reef crest and eastern marina site test cores to investigate:

- The relationship between the Last Interglacial and Holocene reefs
- The sea level and growth history of the Holocene (last 10,000 years) as determined from U-series dating
- The chronology of reef growth onset, duration and termination
- The response of the reef system to past Holocene sea level rise, and the likely response to future sea level change

As a fringing reef, Ningaloo Reef grew during the end stages of the major sea level rise at the end of the last Ice Age during Holocene time (last 10,000 years) under conditions of initial flooding and sea level rise until a Late Holocene highstand at 6,000 years ago of +2 metres, then a fall to present sea level. The stranded lagoons along the coastal plain reflect shoreline retreat during the last few thousand years.

Western and eastern coral reef growth was asymmetrical with respect to its pattern and timing, and the events recorded, probably reflecting differences in topography, wave energy and hinterland interactions. Active western reef flat accretion took place during the slow fall of sea level from about +2m, significantly later in development than the eastern Ningaloo Reef, where growth terminated at 6.8 ka ago, close to the timing of the Late Holocene sea level highstand along the WA coast.

The relationships discovered between reef growth and sea-level fluctuations during the Holocene provide a basis for assessment of the impact of climate and sea-level change on the reef and coastal ecosystems, both past and predicted. Antecedent topography remains an important element of reef landforms and geomorphology

Whilst this study was not designed to address climate change, emerging issues have been reported. Full scale climate change and mitigation assessments need forward management attention.

Growth history studies require significant resources for coring operations. Considering the project's small scale, the rigors of high wave energy operating conditions and the environmental sensitivity of NMP the outcomes are significant particularly when considered on a cost-benefit basis.

1.1. Background

Western Australia has been described as perhaps the best natural laboratory for studying the effect of climate change on shallow-water carbonates (Hallock, 2005) in view of the latitudinal and climatic gradient along the western margin from tropical north to temperate south, which is expressed in both carbonate sediments and biota (Collins, 1988, James et al., 1999, 2004; Collins et al., 2011). Modern and late-Pleistocene coral reef communities exposed along the Ningaloo coastline, provide a unique example in which to investigate the impact of climate change on coral reefs (Greenstein and Pandolfi, 2008). Little research has been undertaken on the morphology and growth history of the Ningaloo Reef to date. Preliminary studies by Collins et al. (2003) revealed two stages of reef growth; a Last Interglacial "Tantabiddi phase" during which a large fringing reef grew in an active stage of Leeuwin Current flow (ca 125 ka U/Th ago), and a "Holocene phase" (last 10,000 years) during which today's reef recolonised the earlier reef (active reef growth during the last 7 ka). For a summary of the growth history of western Australian reefs see Collins (2011).

In the growth history component of this study we add to this previous research by providing a further insight into the Quaternary evolution of the Ningaloo Reef. Importantly, the timing of reef growth events has been established, together with the thickness and pattern of reef growth. We have identified the importance of reef growth characteristics and morphology for the maintenance of reef biodiversity, and provide an understanding of reef conditions and environmental change over evolutionary timescales. This information is timely considering the current global decline in coral reefs, and will allow marine park management to make more informed decisions on the NMP during a period of likely future change.

Climate change and its detrimental effect on coral reefs has been widely reported (Hoegh-Guldberg, 1999; Hughes et al., 2003; Hallock, 2005; Hoegh-Guldberg, 2006; Hoegh-Guldberg et al., 2007; Wilkinson, 2008). Major environmental change and associated reef response may include (1) increased sea surface temperatures resulting in coral bleaching, disease and mortality, increased bioerosion, and ecological range shifts; (2) rising ocean acidification slowing coral calcification and reef growth; (3) rapidly rising sea-level with slower growth of deeper corals or reef 'drowning', loss of coastal protection and shoreline flooding with increased sedimentation and decreasing water quality; and (4) increased severe storms and cyclones with the physical destruction of corals, modification of communities, increased erosion and sediment transportation (see Twiggs and Collins (2010) for detailed literature review). Environmental changes are likely to act synergistically to reduce coral populations having dramatic consequences for coastal biodiversity, protection and socio-economic implications (Hoegh-Guldberg, 2006). Some reefs may adapt with strategies such as reef flat reactivation and back-stepping of corals to shallower substrates during rapid sea-level rise.

Predicting how reefs may respond to environmental change is difficult due to the lack of long-term ecological data (Pandolfi and Greenstein, 2007). Consequently the fossil record provides us with an insight into the nature and rates of past change, which is increasingly relevant for assessing future coral reef response. Reef coring and dating studies are designed to evaluate the history of reef growth and morphology in relation to environmental change on long-term timescales.

1.2. Objectives

The overall aim of WAMSI Project 3.4 was to determine the geomorphological and sedimentary characteristics (biological and physical) of the Ningaloo Reef and shelf, and to identify evolutionary characteristics relevant to the maintenance of marine biodiversity and likely climate change impacts. This included characterising reef growth history, coastal and seabed geomorphology, surficial sediment facies and their influence on the distribution of benthic habitats.

The growth history component (3.4.1) was to specifically characterise the morphology and growth history of the Ningaloo Reef system. This objective is reflected in the following management related question that was posed:

- Does the morphological history of Ningaloo Reef and surrounding areas provide an insight into and predictive capacity for potential and future climatic changes?

To approach this question an investigation was undertaken on the northern Ningaloo Reef on both the west and east sides of the Cape Range to determine the:

- relationship between the Last Interglacial and Holocene reefs;
- sea-level and growth history of the Holocene reef (last 10,000 years);
- chronology of reef growth initiation, development and demise;
- Holocene reef development and biofacies relationships; and,
- response of the reef system to past environmental change including sea-level rise, and the likely response to future changes.

This research was of a reconnaissance nature and is by no means a comprehensive study of the whole of the reef tract, nor was it designed specifically as a climate change study, but it has provided fundamental information on reef growth history and a potential analogue for the assessment of reef development during environmental change on coral reefs, insights that are useful for climate change assessments.

1.3. Methods

During May 2008, a shallow coring program was carried out within the northern section of the high energy and wave-exposed western Ningaloo Reef. The approach was to obtain core from the reef flat to reef crest. Due to the sensitivity of the reef environment (access limitations, together with financial constraints) only lightweight portable coring equipment could be deployed. The equipment has the advantage of being able to be deployed using a small dinghy and four operators, but the disadvantage of requiring shallow (waist-deep) water and relatively calm conditions for safe operation. As the reef flat is subject to surge action from swell waves at most parts of the tidal cycle, with the exception of low tide, two weeks in the month of May were selected since this period offered a reasonable prediction of low swell conditions accompanying spring tides. Three sites selected for reef flat coring were at Osprey, Bundera and Winderabandi (Figure 1.1)

To investigate the contrasting low energy and sheltered reef environments of the Exmouth Gulf, a core transect was obtained from the Department for Planning and Infrastructure (DPI) undertaken during a geotechnical investigation of the Exmouth marina site in 1995.

Figure 1.1 – Drill sites at A: Osprey and B: Winderabandi

For both the western and eastern Ningaloo Reef, contemporary reef and coastal geomorphology were investigated using hyperspectral remote sensing imagery and bathymetric data, and reef community assessments were undertaken during qualitative snorkelling surveys to provide modern analogues for fossil reef communities. All cores were logged for stratigraphy of major reef units including sediment/rock types, boundaries and hiatuses; primary, secondary and associated reef builders; and other physical features such as calcrete (secondary carbonate) horizons and borings. Bio-lithofacies were described according to the growth form of primary framework builders and non-framework detritus, and fossil corals were identified to genus level where possible. Coral samples were selected for dating by high precision U-series thermal ionization mass spectrometry (TIMS) at the University of Queensland (UQ). Vertical accretion rates were obtained using U-series dated material in relation to the thickness of the deposited carbonates (i.e. in-situ coral framework and detrital units).

To place the development of the Ningaloo Reef into context, a comparison has been made with a modified Houtman Abrolhos sea-level curve (Collins et al., 2006; Twiggs and Collins, 2010). The relationship between reef growth and sea-level fluctuations during the Holocene provides a basis for the assessment of the impact of climate and sea-level change on the reef and coastal ecosystems. Further detail on methodology is provided in WAMSI milestone reports and Twiggs and Collins (2010).

The late-Pleistocene and Holocene growth history and chronology have been determined for the contrasting conditions of the wave-exposed western Ningaloo Reef and the relatively protected and lower energy condition of the eastern Ningaloo Reef in the Exmouth Gulf.

1.4. Findings

1.4.1. Western Ningaloo Reef

The most successful coring was achieved at Osprey, where 8.4 m of Holocene reef was cored from the inner reef flat, and Winderabandi, where 4.7 m of Holocene reef was intersected. However, core recovery percent was low in both cases. The Last Interglacial reef (125 ka reef) was penetrated at the base of each hole.

The Holocene reef has grown to current sea-level (see sea-level curve in Figure 2.2) characterising it as a ‘catch up’ reef. Reef growth is significantly later in development than the eastern Ningaloo Reef (see results below), where growth terminated at 5.8 ka after the mid-Holocene sea-level highstand of +2 m along the WA coast. Thus active reef flat accretion after the Holocene highstand at Winderabandi and Osprey would have taken place during the slow fall of sea-level (Holocene regression) from about +2 m, and this is likely to be a regional occurrence (see Figure 1.2).

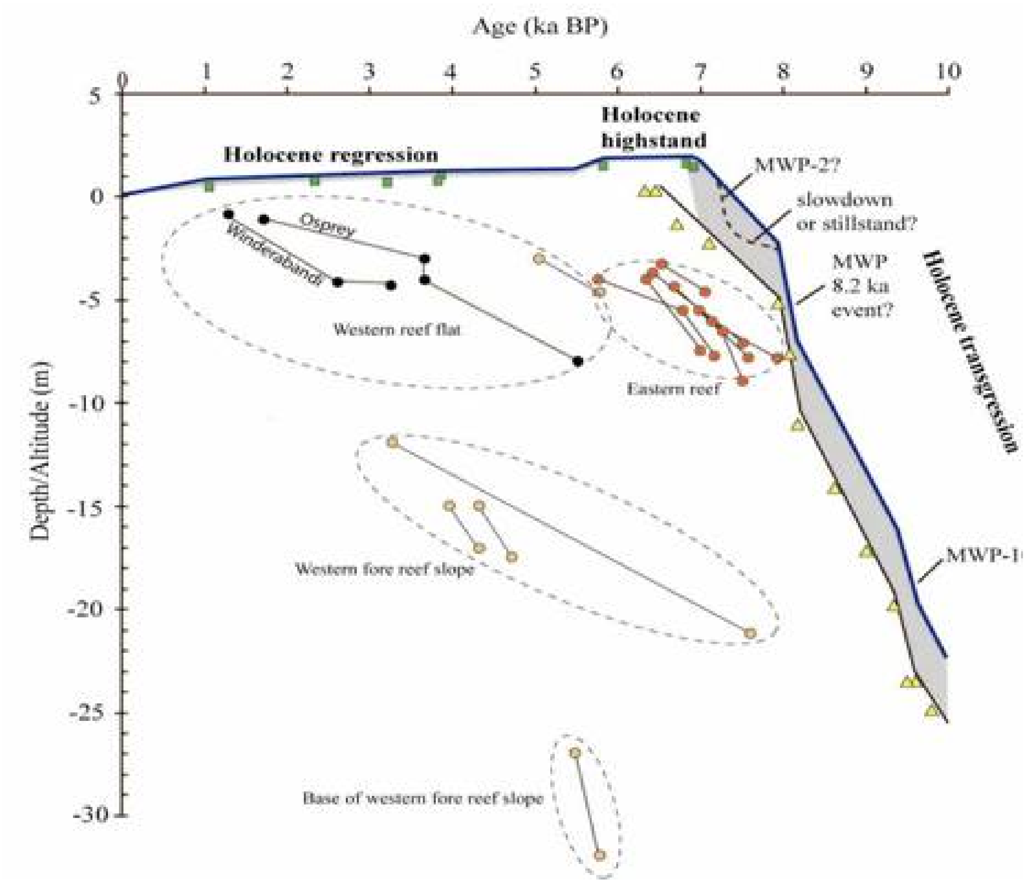

Figure 1.2 - Compilation of Ningaloo Reef Holocene geochronology and growth history data, compared with Houtman Abrolhos data corresponding to a “catch- up” pattern of reef growth. Blue line represents interpreted sea-level curve for the WA coast. Note that reef crest data are not available for Ningaloo Reef. Data sources: Houtman Abrolhos: Collins et al., 2006; eastern reef: Twiggs and Collins, 2010; western reef; Collins et al., 2003; western reef flat: WAMSI Project 3.4 Final Report.

There are important contrasts between the Winderabandi site (reef flat, near the reef crest) and the Osprey site (most landward part of the reef flat), particularly in terms of Holocene reef thickness (4.7m at W2; 8.4m at O3; see section 3 for locations). Assuming that both hole bases indicate the elevation of the underlying Last Interglacial reef surface (which is represented by a prominent "step" in the reef wall within a trough immediately seaward of the W2 site, and has also been seismically mapped elsewhere, as well as outcropping in coastal terraces at both sites) the Last Interglacial surface is elevated near the reef crest (at W2) and is deeper to landward at O3, then shallows to become emergent by up to 2 m at the coast. Differing reef growth initiation ages (=basal dates in cores) would be determined by different drowning ages for this irregular surface as sea-level rose during the Late Holocene, and it seems likely that the position of the western reef crest was controlled by the Last Interglacial reef, similar to the model shown in previous coring at Tantabiddi (see Collins et al., 2003). Whilst the influence of Last Interglacial reef substrate provided a regional control on Holocene growth along the length of Ningaloo Reef, Pleistocene alluvial fans which built out from the coast near "gorges" such as at Yardie Creek also provided antecedent surfaces for reef colonisation and locally control Holocene reef morphology.
Following reef flat accretion to close to present levels and sea-level stabilisation, energy regimes across the reef flat would have also stabilised, leading to the modern reef community which most likely reflects those conditions (see Cassata and Collins, 2008). The core dates indicate that there has been little/no reef growth during the last 2 ka which may suggest that modern reef flat communities are currently veneer, with limited reef building occurring vertically due to the lack of accommodation (space) for growth to occur. This also suggests a balance of constructive (reef growth) and destructive (e.g. erosion) processes. Lateral growth of the reef crest seaward may be occurring.

The geomorphic zonation of the northwestern Ningaloo backreef strongly influences the zonation of modern habitats and communities. For further description of these refer to WAMSI Project 3.4.2, WAMSI reports and Cassata and Collins (2008).

1.4.2. Eastern Ningaloo Reef (within Exmouth Gulf)

Analysis of the internal structure of the eastern Ningaloo Reef has provided a clear insight into Holocene reef growth during environmental change that can be used to assess future pressures on coral reef ecosystems globally (see Chapter 4, Twiggs and Collins, 2010).

The Ningaloo Reef within the Exmouth Gulf becomes increasingly incipient where it is best described as a submerged reef that lacks a defined reef flat. This morphology appears to be in part related to a marked change in oceanographic conditions and an increase in turbidity in the Gulf, which can affect coral community composition and ultimately carbonate accumulation.

The Last Interglacial reef provided the substrate for Holocene reef initiation and further influenced reef accretion rates, facies development and reef morphology. Two Holocene reef provinces, the inner and outer reef zones accreted above the Last Interglacial foundation. Eight Holocene reef facies (total thickness of 1.8–5.3 m) included coral framework facies (domal, arborescent, mixed, tabulate and encrusting) and detrital facies (carbonate sand, skeletal rubble and alluvial fan deposits). Distinct reef facies associations occur both vertically and laterally, reflecting changing Holocene environmental conditions in this low energy, sheltered to semi-exposed setting.

- Encrusting corals grew only during reef initiation on the outer reef slope in palaeodepths of ~6.5 to 7 m.
- Domal corals with or without coralline crusts grew only on the outer reef in palaeodepths of ~5 to 8.5 m with the highest rates of accretion and thickest accumulation.
- Arborescent corals grew on shallower and/or more sheltered settings on the outer and inner reefs in palaeodepths of ~3 to 9 m. This facies was highly influenced by erosion from severe storm/cyclone activity forming skeletal rubble.
- Mixed coral facies grew in palaeodepths of ~4.5 to 9 m and were common during reef "start-up" and prior to reef "give-up" in periods that may have experienced higher sedimentation and increased turbidity, suggesting a more stress tolerant coral facies.

Holocene ages range from 7.93 to 5.8 ka BP with vertical accretion ranging from 1.46 to 9.88 mm/year (avg. 4.11 mm/year). Highest rates of accretion and thickest accumulation occurred in the most seaward and deepest cores composed of massive coral framestone and coralline algal crusts.

A six stage chronology of Holocene reef accretion and facies development in relation to fluctuating sea-level is proposed (Figure 1.3), including:
1) Coastal inundation from 8 to 8.5 ka BP,
2) Initiation 'start-up' from 8 to 7.5 ka BP,
3) Rapid growth 'catch-up' and back-step from 7.5 to 7 ka BP,
4) Rapid aggradational growth 'catch-up' from 7 to 6.5 ka BP,
5) Reef decline 'give-up' and detrital buildup from 6.5 to 5.8 ka BP, and
6) Detrital buildup and progradation from 5.8 ka BP to present.

The Holocene reef deposited through aggradation and back-stepping during the Holocene sea-level transgression with minor accretion during the subsequent Holocene highstand, finally ceasing growth during the onset of the late-Holocene sea-level regression. The reef was not able to 'keep-up' with sea-level despite the available accommodation and as a consequence formed an incipient reef

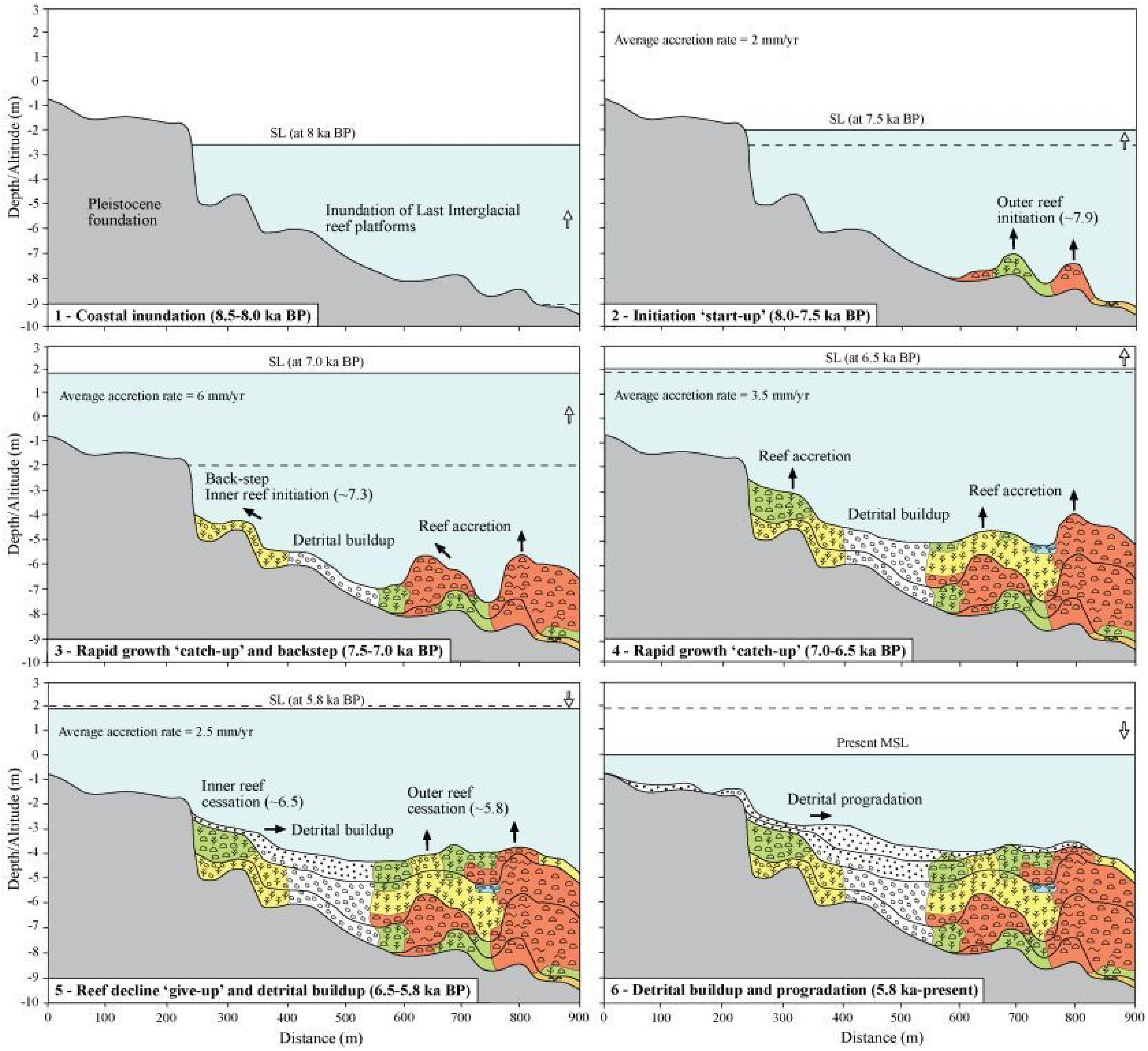

Figure 1.3. Chronology of reef and facies development from 8.5 ka BP to the present, Exmouth Gulf, WA. Refer Twiggs and Collins, 2010 for reef facies legend and details of isochrons (solid lines); colours or grey shades correspond to particular facies and illustrate changes during the Holocene. Solid arrows refer to the nature and direction of accretion. Sea-level data is based on the composite sea-level curve of WA (see Twiggs and Collins, 2010).

morphology throughout its evolution. Changes in reef facies and the ultimate demise of the Holocene reef probably involved a combination of increased sea-level, coastal flooding and erosion during the mid-Holocene highstand, with associated increase in sedimentation, turbidity and decline in water quality; burial by sediment buildup during the mid-Holocene highstand and detrital progradation during the mid- to late-Holocene regression; and, the introduction of alluvial sediment during cyclones and other severe storms to an already stressed environment. Modern communities have thus shifted from coral-dominated to bored macroalgal pavements.

The contemporary submerged reefs lining the western Exmouth Gulf may represent a mixture of reef ‘turn-ons’ and ‘turn-offs’ (Buddemeier and Hopley, 1988; Kleypas, 1996) at various growth stages, including incipient reefs with coral reef communities that have not yet grown to present sea-level; veneers of non-reef-building coral communities on exposed relict surfaces; or, as this marina transect study has illustrated, reefs that developed earlier in the Holocene and were later turned-off by environmental changes shifting to algal dominated states. The effect of environmental disturbance on coral reefs due to climate change and other anthropogenic stresses may depend on which growth type a particular reef represents.

2. Key Findings and Recommendations

2.1. Objectives and Outcomes – Key Findings

The growth history component (3.4.1) was to specifically characterise the morphology and growth history of the Ningaloo Reef system, to provide an insight into and predictive capacity for potential and future climatic changes. Whereas little was previously known about the timing of Holocene reef growth, the chronological framework developed in this study shows the contrasting pattern of eastern and western reef development, with the persistence of western reef flat growth into the late-Holocene. The importance of antecedent topography and the control exerted by the Last Interglacial phase of reef growth over modern reef morphology have been confirmed by the coring results. The study of site test cores taken through shallow reef environments seaward of the Exmouth marina within the Exmouth Gulf, yielded high quality information on the growth history of the eastern Ningaloo Reef (see Twiggs and Collins, 2010). The relationship between reef growth and environmental change during the Holocene provides a basis for assessment of the impact of climate and sea-level change on the reef and coastal ecosystems.

2.1.1. Significance of Antecedent Topography

Ningaloo reef is an “overprint” built upon pre-existing topography which remains as a significant landform influence in the form of:

- Widespread raised reef platforms along the coast and their eroded rock platform equivalents (last interglacial remnants).
- “Canyon” associated carbonate alluvial fans which form substrates for Holocene reef morphology and growth (e.g. at Yardie Creek)
- substrates for earlier (last interglacial) reef growth (e.g. at Mowbowra) and Holocene reefs in general
- the sinuous ridge which meanders N-S along the western coastal plain is the leeward expression (shoreline) of the last interglacial transgression.

2.2. Implications for Management - Recommendations

The geoscientific research undertaken in this project has been wide ranging in scope and whilst it represents an overall advance in knowledge much remains to be investigated in detail when the size and scale of the Ningaloo Reef region is taken into consideration, particularly when balanced against the research resources available. Whilst much of the analysis in WAMSI Project 3.4.1 has focused on the provision of baseline information, it links closely to the biodiversity projects within Node 3 and provides a basis for a further generation of management oriented research. Studies such as the Caring for Country Project to be undertaken in the Shark Bay World Heritage area during 2011-12 (co-ordinated by WAMSI) will provide a template for potential future management oriented investigations. This project will investigate the impacts of predicted climate and sea-level change on ecological assets for future management planning. Similar studies will be needed for the Ningaloo region.

The evolutionary perspective shows that the Ningaloo Reef has experienced environmental change, including sea-level fluctuations that were likely at similar, if not at greater magnitudes than those projected with climate change for the mid-west region. The study of a section of the eastern Ningaloo Reef also demonstrates that a combination of natural processes (fluctuating sea-level, flooding, increased sedimentation and turbidity, alongside severe storm activity) likely contributed to changes in reef accretion and biological communities, and the ultimate demise of the reef during the mid-Holocene. However, the differing evolutionary history between eastern (embayment coast) and western (oceanic coast) fringing reefs should also be noted when considering future trends, although much more data remains to be collected along the western reef tract.

Impacts of the greatest concern to coral reef ecology and geomorphology include increases to sea surface temperatures, sea-level, ocean acidity and storm severity. Maintaining the resilience of coral reefs after disturbances (e.g. cyclone impacts or flooding) is central for the preservation of these ecosystems in ecological timescales (Hoegh-Guldberg, 2006). Geomorphology is uniquely positioned to offer an integrative perspective of reef condition that is at a scale appropriate for many climate change assessments (Smithers et al., 2007). The issue of the climate change future of the Ningaloo region is of significance for Marine Park (and potential World Heritage) management as significant changes may occur to community composition, reef accretion and geomorphology of the reef system and coastline. Smithers et al. (2007), provide a detailed review of potential impacts of climate change on the geomorphological structure of the GBR, relevant to the management outcomes of this study.

This study integrating reef development processes with the response to environmental change has provided an insight into the effect on the growth history, geomorphic and sedimentary evolution and biological communities of sections of the eastern and western Ningaloo Reef system. This provides analogues for the assessment and prediction of future change, enabling natural resource management to adapt their management strategies of the reserves accordingly. Adapting management will include promoting mitigation and supporting resilience as suggested by recommendations for the GBR (Marshall and Johnson, 2007; Smithers et al. 2007). The results from this study provide both baseline information and a blueprint for future research and monitoring and specific recommendations as they relate to scenarios and management strategies are detailed below.

2.3.1. Management Frameworks

With predictions of greater intensity of rainfall events (severe storms/cyclones) and increases in sea-level during climate change, with an associated increased risk of coastal erosion, storm surge and flooding (CSIRO, 2007), stringent controls need to be in place for the management of coastal development to preserve values and assets. This research will assist in terrestrial planning for infrastructure, providing assessments of suitable and unsuitable sites for development and/or infrastructure that need to be identified using (with other criteria) a geomorphological approach. The potential interactivity between terrestrial environments (including natural systems and infrastructure-related changes) and the nearshore marine systems will need careful consideration. Cyclone Vance in 1999 provides an example of severe storm impact. One infrastructure issue was the flooding of the coastal sewage treatment facility south of Exmouth, with potential return of nutrient laden waters to the marine environment. The subsequent construction of expanded sewage treatment facilities at coastal Coral Bay also carries similar future risks especially in the case of increased event frequency/intensity.

2.3.2. Management Intervention

Models for predicted climate change are likely to become more precise and more region-specific as they continue to develop. Among the critical factors will be changing intensity of rainfall and storm/cyclone events and rising sea-levels over a 50-100 year timescale. An understanding of potential effects of climate change from this study will enable adaptive management of the marine and terrestrial reserves accordingly, focusing efforts on mitigation and resilience. Impacts associated with predicted rises in sea-level and intensity of storm/cyclone events, including coastal wave energy, coastal sediment transport, changes in beach form and/or loss of beaches and beach amenities, flooding, changes in water quality/turbidity, burial of reef communities by sediment buildup and groundwater impacts (see Project 3.10 for further discussion), will need to be further understood and monitored.

State Coastal Planning Policy now factors in a sea-level rise of 0.9 metres by 2100; this is equivalent to up to 90 metres of coastal retreat on a sandy coast. The greatest erosion potential exists for the sandy coasts (often localised as cuspate forelands such as Turquoise Bay and Winderabandi) which are lower in proportion than rocky shores but frequently have the highest recreation focus and tourism potential. Concurrent ecological impacts will occur, for example loss of turtle nesting beaches. Sand loss from more stable rocky shores is likely to result in greater exposure of these lithified shorelines which constitute a larger percentage of the Ningaloo coast and which may also provide the substrate for coral reef communities to 'back-step' during (low probability) rapid and potential 'jumps' in sea-level. Back-stepping of reefs to shallower substrates during rising sea-level is well known where coral growth can keep-up or catch up with the rates of change.

Increases in sea-level and intensity of storms/cyclones will also bring potential impacts on reef communities and accretion. Impacts may include higher hydrodynamic energies across reef flats, through reef passes and in lagoons with greater destructive forces operating in these settings which may significantly influence coral communities and reef development. The more rapid projections of future sea-level rise also may reinvigorate or ‘turn on’ reef accretion by providing new accommodation (space) into which corals may grow (Smithers et al, 2007). Coral shingle formed from the physical destruction of coral is an important contributor to many geomorphological features (eg beaches), and may be a major and relatively dynamic producer of coral sands. Geomorphological features and associated communities reliant on sediments will be sensitive to any structural transformation (Smithers et al, 2007).

Identifying underlying geomorphic features that are important for reef habitats and beach development can be used to highlight vulnerable areas that may require additional protection with increasing human pressures (e.g. important lagoonal habitats, effect on turtle nesting beaches etc.). As calcification rates are also likely to decrease as a result of acidification and bleaching events through increased SST, consequences such as increased bioerosion intensity are expected, the interaction of such changes may need future evaluation.

Increasing the resilience of coral communities to adapt to change by reducing anthropogenic and natural stresses from changes to factors such as water quality and development is likely to be important wherever possible. As future land use patterns change in association with tourism development or coastal industrial activities change, the present low level of impacts from terrestrial activities to the marine environment may also change. Water quality impacts will need to be carefully managed by reducing additional local anthropogenic pressures from coastal development, or any issue that impacts on water quality/turbidity (e.g. dredging activities in Exmouth Gulf).

Groundwater impacts from flooding and sea-level change need careful attention and ecological evaluation. For a detailed discussion of the Ningaloo groundwater system and related research please refer to the progress and final reports of WAMSI Project 3.10.

2.3.3. Education

Information for public education programs regarding reef history and growth and the impacts of global patterns such as climate change can be generated from research findings using cross-referenced outcomes, public presentations and suitable onsite signage. Promotion of communication and awareness to local users, tourists and industry should be a developing priority as an investment tool for reducing local reef dependent tourism impacts and carbon footprints, further improving reef resilience to change. Regardless of whether or not World Heritage listing occurs such activities need to be proactively developed as part of management strategies.

2.3.4. Research and Monitoring

Within the constraints of a limited budget significant findings have been made on the growth history and evolution of the Ningaloo reef system and its consequences for biodiversity. The research has provided managers with an understanding of the chronology of reef growth and the potential future impacts of climate change and provided a framework of benefit to adaptive management of marine and terrestrial reserves and their assets. The information documented on the physical domain and historical changes is relevant to predictive models for environmental and climate change.

However, much geoscientific work remains to be done before our knowledge of the Ningaloo system can be compared with, for example, the information assembled for the Great Barrier Reef. Compared to Project 3.4, a much greater research investment is required. Examples of future research/monitoring to address knowledge gaps to aid in managing climate change impacts, could include the following:

- Additional reef growth studies to understand sea-level history specific to Ningaloo and reef response during Holocene evolution (including community structure, storm/cyclone occurrence). May include detailed core transects across the western reef and lagoon with comparisons to modern assemblages already characterised in geomorphic zones as part of project 3.4.2.
- Reef growth studies to understand the organisms and processes involved in reef development (including seismic, coring and geochronological studies) and accretion studies (e.g. specific communities, erosional processes, binding organisms etc).
- Establishing accurate palaeohistories of storm occurrence and tsunamis along the coastline.
- Additional coral community assessments in different geomorphic settings on the entire Ningaloo coast.
- Monitoring of modern communities for changes - using Project 3.4.2 inshore work as a baseline.
- Understanding and ongoing monitoring of sediment budgets of the Ningaloo Reef system, including lagoonal and coastal sites, and links to landforms and processes.
- Development of coastal risk and change models based on a range of predicted sea-level changes for the area.

- Identification of sites for conservation management based on geomorphological history and growth stage, and sites most geomorphically resilient to climate change impacts.
- Monitoring of calcification and accretion rates, including *Porites* palaeoenvironmental analysis.
- The significance of spatial variations in geomorphological sensitivity and vulnerability to the effective management of critical organisms and habitats.
- Establishment of a marine and terrestrial GIS of the whole system for research, mapping, land use planning, monitoring and management.
- Monitoring of water quality, sedimentation and turbidity.

The use of Geographic Information databases and systems (GIS) in coastal and shallow marine management requires further attention. Prior to the Node 3 projects Curtin mapped the Ningaloo coast and provided a coastal GIS of geomorphology, access and land use for terrestrial management. It is now time to build a linked GIS system covering the nearshore reef and lagoonal environments along the entire Ningaloo coast to accommodate increasing tourism activities and possible changes to coastal land use and tenure as an aid to assist coastal managers. Such a system would facilitate Identification of underlying features related to habitat development that can be used to highlight vulnerable areas that may require additional management with increasing human pressures. GIS based maps of geomorphic and physical features can be used for planning management activities and targeting and recording management interventions, including protecting key biodiversity that is important for conservation of reef-building communities and developing coastal planning and risk assessments for climate change.

2.3. Other Benefits - Published and Ongoing Work

The project results have advanced the understanding of reef geomorphology and growth history for Ningaloo, and a number of papers have been published describing the project's findings:
The paper by Twiggs and Collins (2010) summarises project findings for the eastern reef. Related papers are more broadly based and draw on some of the projects findings:

Cassata, L., Collins, L.B., 2008. Coral reef communities, habitats, and substrates in and near Sanctuary Zones of Ningaloo Marine Park. Journal of Coastal Research: Vol. 24, No. 1 pp. 139–151.

Twiggs E.J., and Collins L.B. 2010. Development and demise of a fringing coral reef during Holocene environmental change. Marine Geology 275, 20-36.

Collins L.B., 2011. Controls on morphology and growth history of coral reefs of Australia's western margin. *In* Morgan, William A., George, Annette D., Harris, Paul M. (Mitch), Kupecz, Julie A., and Sarg, J.F. (eds.), Cenozoic Carbonate Systems of Australasia, SEPM, Special Publication 95. (in press)

Collins, L.B. 2011: Reef Structure. In: David Hopley (ed.) Encyclopedia of Modern Coral Reefs, Springer.

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2.4. Problems Encountered

The project represented only a part of 3.4 activities and was ambitious in scope and undertaking given the budget available within the overall biodiversity emphasis of Node 3, together with the length of the reef tract and operating constraints due to high wave energy. The deployment of lightweight portable drilling equipment on the exposed western reef had limitations in terms of operating conditions and core recovery, minimal environmental footprint requirements and safety factors.

Opportunistic use of eastern marina site test cores proved fruitful and was reliant on generous collaboration provided to the project leader. Given there was a significant project overspend in the research and the benefit provided by access to the expensive marina core the outcomes are significant on a cost/benefit basis.

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3. Reef Geomorphology and Growth History – Western Ningaloo Reef

3.1. Introduction

Core studies of the reef growth history are designed to evaluate the history of reef growth in relation to sea level change on long term timescales as part of assessments of the geomorphic structure of the reef and its relation to earlier stages of reef growth. This information will provide linkages between benthic habitat and substrate data and the ancestral reef features which often influence present day biodiversity.

Western Australia has been described as perhaps the best natural laboratory for studying the effect of climate change on shallow-water carbonates (Hallock, 2005) in view of the latitudinal and climatic gradient along the western margin from tropical north to temperate south, which is expressed in both carbonate sediments and biota (Collins, 1988, James et al., 1999, 2004; Collins et al., 2011). Modern and late-Pleistocene coral reef communities exposed along the Ningaloo coastline, provide a unique example in which to investigate the impact of climate change on coral reefs (Greenstein and Pandolfi, 2008). Little research has been undertaken on the morphology and growth history of the Ningaloo Reef to date. Preliminary studies by Collins et al. (2003) revealed two stages of reef growth; a Last Interglacial "Tantabiddi phase" during which a large fringing reef grew in an active stage of Leeuwin Current flow (ca 125 ka U/Th ago), and a "Holocene phase" (last 10,000 years) during which today's reef recolonised the earlier reef (active reef growth during the last 7 ka). For a summary of the growth history of western Australian reefs see Collins (2011).

In the growth history component of this study we add to this previous research by providing a further insight into the Quaternary evolution of the Ningaloo Reef. The main goal of this study component is to improve the understanding of the subsurface geomorphology and pattern of reef growth through time by core studies tied to seismic profiles and supported by geochronology and isotope analysis.

Importantly, the timing of reef growth events has been established, together with the thickness and pattern of reef growth. We have identified the importance of reef growth characteristics and morphology for the maintenance of reef biodiversity, and provide an understanding of reef conditions and environmental change over evolutionary timescales. This information is timely considering the current global decline in coral reefs, and will allow marine park management to make more informed decisions on the NMP during a period of likely future change.

3.1.1. Background

3.1.1.1. *Regional Geology*

The NMP lies across the boundary of the Northern and Southern Carnarvon Basins with the majority located in the Exmouth Sub-Basin of the Northern Carnarvon Basin (Fig. 3.1). This large Palaeozoic-Recent mainly offshore basin, on the Northwest Shelf, is Australia's premier hydrocarbon province where the majority of deepwater wells have been drilled (greater than 500m depth). The Tertiary Cape Range Anticline is one of the dominant features of the terrestrial landscape of the Exmouth Sub-Basin and the Muiron Islands, to the north-east, are recognised as extensions of the anticline. Cape Range, Ningaloo Reef and Exmouth Gulf, are underlain by thick sedimentary sequences ranging from Palaeozoic to Holocene in age (van de Graaff et al. 1980; Hocking et al. 1983; Collins et al. 2006). Emergent, tectonically warped terraces overlying mid-late Tertiary units are present on the western side of Cape Range (Wyrwoll et al., 1993). The youngest terrace, the Tantabiddi, is of Last Interglacial (LI) age (ca. 125 ka; Stirling et al., 1998) and lacks deformation, attesting to the tectonic stability of the region since that time. The Tantabiddi precedes the present day Ningaloo Reef and represents a far larger reef system (Collins et al, 2003) with outcrops along the modern shoreline and underlying the coastal plain (Fig. 3.2). The continental slope and shelf comprise the Northern Carnarvon Ramp (formally the Dirk Hartog Shelf) to the west of the Cape Range peninsula, Rowley Shelf to the north-east and Exmouth Gulf to the east.

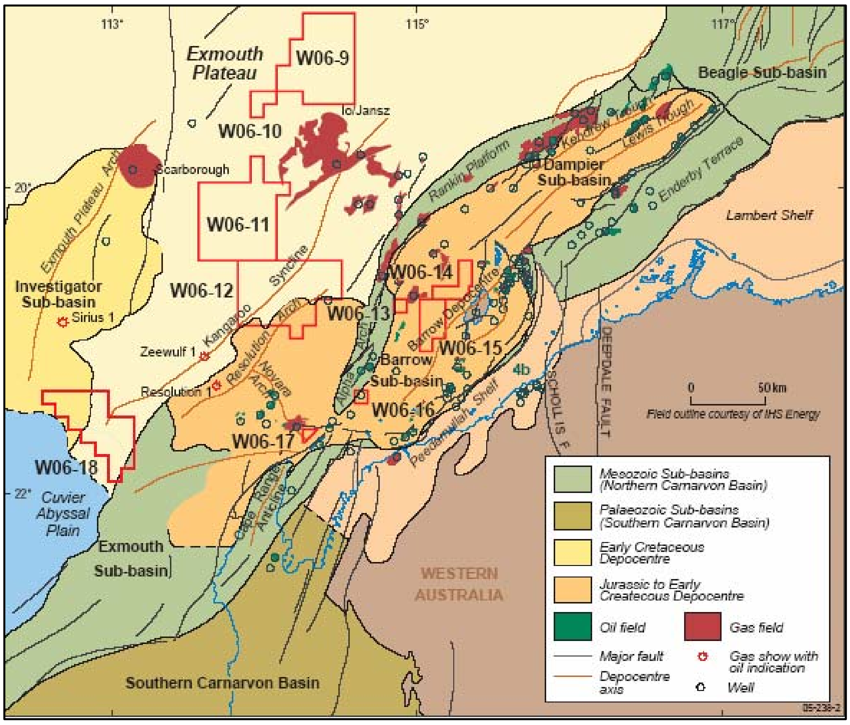


Figure 3.1: Structural elements of the Carnarvon Basin. From (Offshore Acreage Release, 2006)

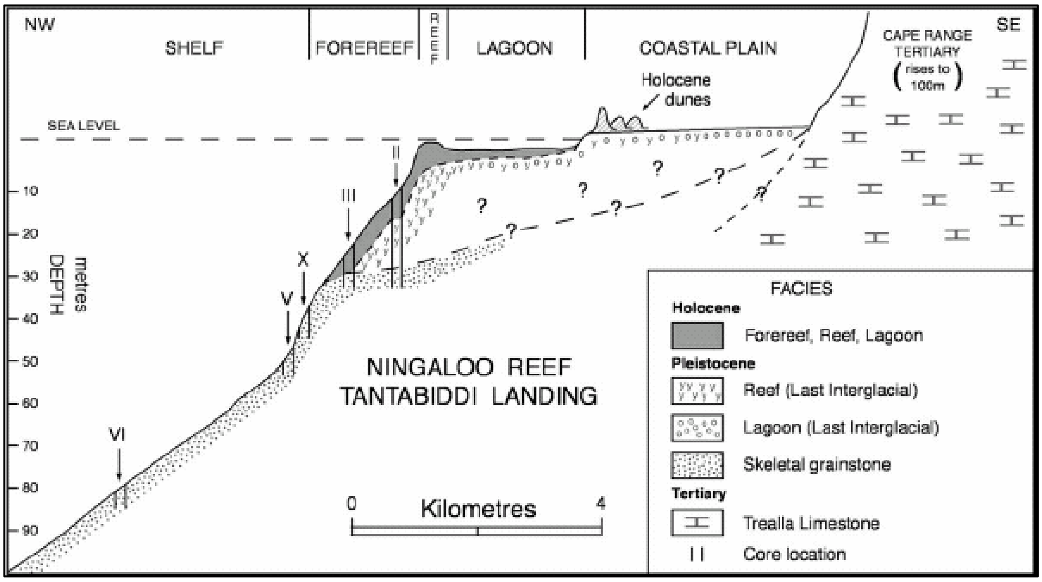


Figure 3.2: Idealised northwest-southeast cross section of northern Ningaloo Reef based on the cored transect and seismic data at Tantabiddi (Collins et al. 2003).

3.2. Materials and Methods

3.2.1. Western Reef

3.2.1.1. *Equipment*

During May, 2008 a shallow coring program was carried out within the northern part of Ningaloo Reef. The coring equipment consisted of a hand-held rotary drill head and attached drillstring, supported by a dinghy-mounted power-pack consisting of a hydraulic motor and water pump. The system required 4 operators and was deployed in shallow reef environments. The approach to obtaining core from the reef flat to reef crest at Ningaloo Reef was limited by safe operational and feasibility constraints.

Due to the sensitivity of the reef environment, limitations to coastal access for dinghy and equipment launching, together with financial constraints, lightweight portable coring equipment only could be deployed.

The equipment has the advantage of being able to be deployed using a small dinghy and four operators, but the disadvantage of requiring shallow (waist-deep) water and relatively calm conditions for safe operation.

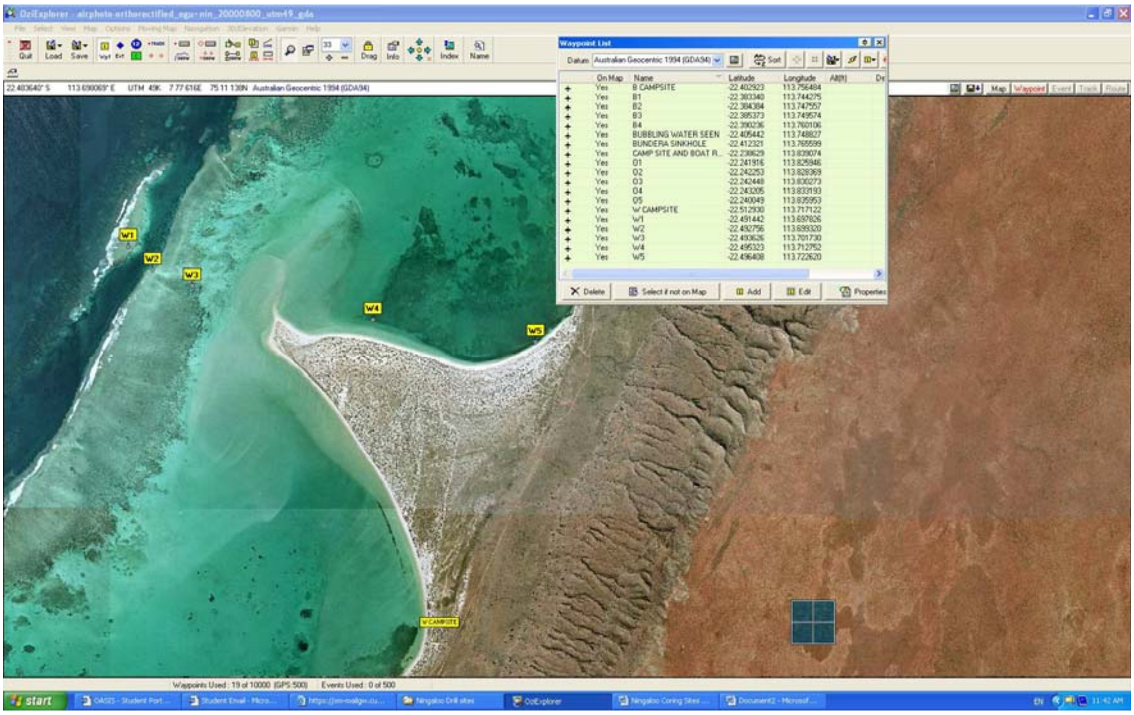
As the reef flat is subject to surge action from swell waves at most parts of the tidal cycle, with the partial exception of low tide, 2 weeks in the month of May were selected since this period offered a reasonable prediction of low swell conditions accompanying spring tides, thus providing the best chance of favourable operating conditions in a normally energetic environment. However, the significant swell waves experienced limited operational opportunities and capabilities.

3.2.2. Site selection

Three sites selected for reef flat coring were at Osprey, Bundera and Winderabandi. The sites were chosen for reasons of beach access availability, and potential for attenuated wave conditions. The location of planned core traverses and site survey descriptions are given below; potential core sites are shown in yellow.

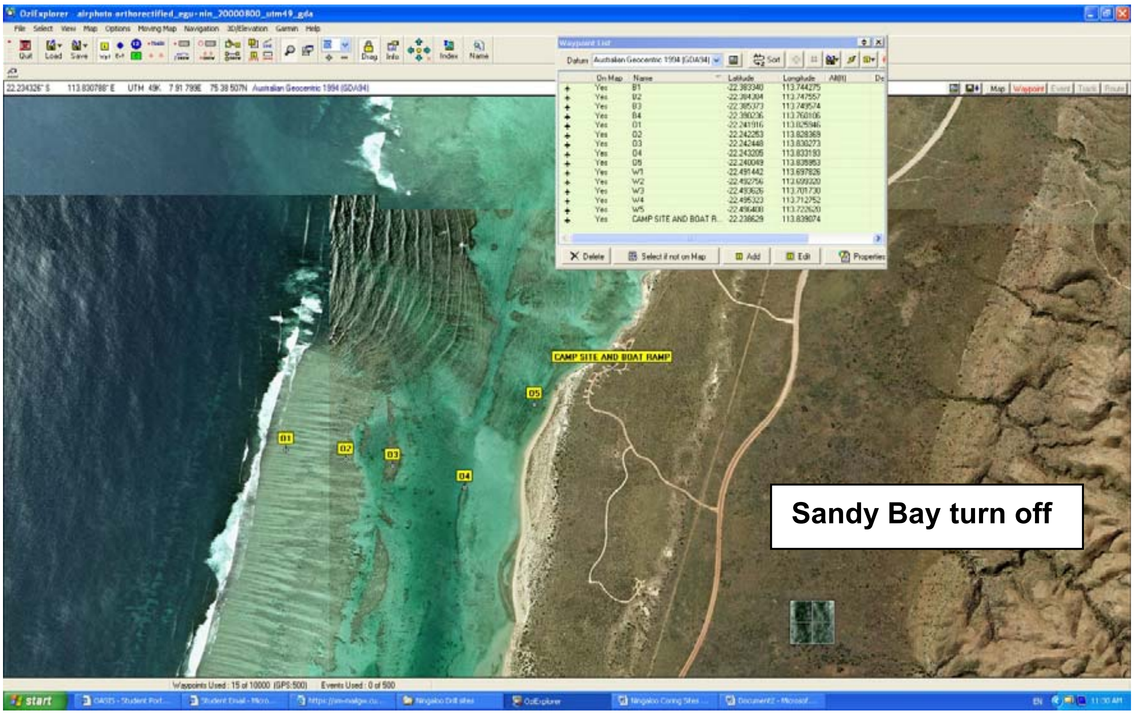
Winderabandi SZ

Access is via a sandy track to the beach for boat launch, then about 900m to a gutter delineating a primary and secondary reef crest, ensuring calm operating conditions in a relatively seaward position, with good potential for drilling reef flats.



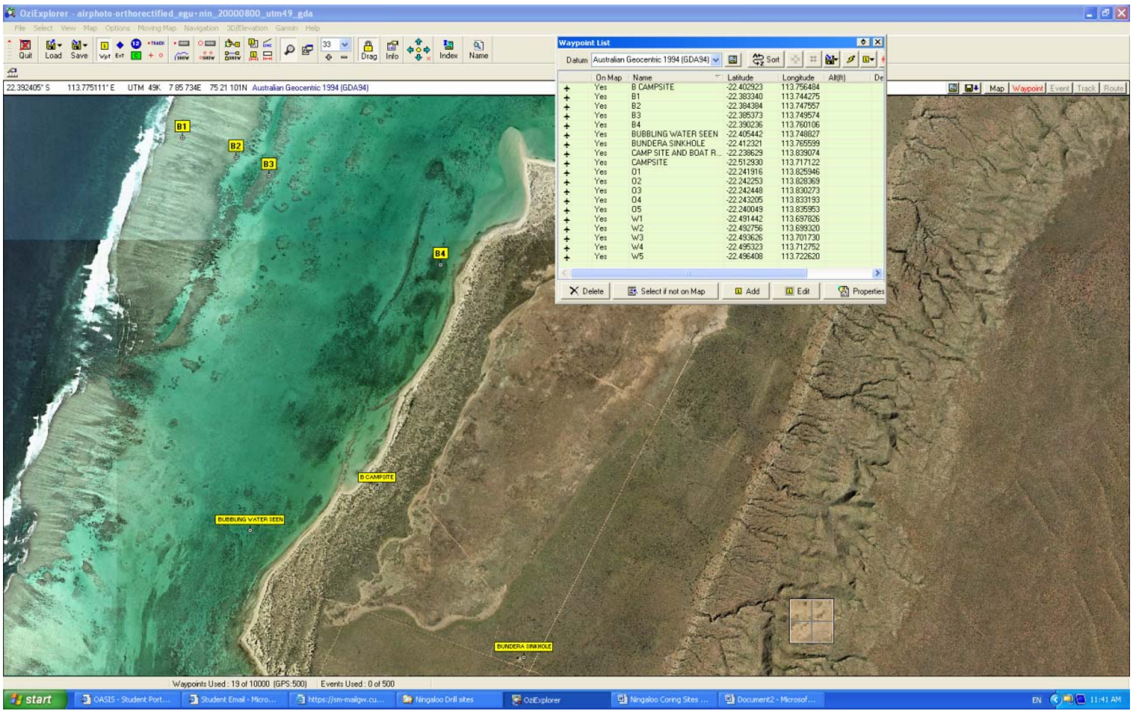
Osprey SZ

There is access from a campsite at Osprey via a boat ramp (very steep and sandy). It is calm in the lagoon especially in the gutters that run through both lagoon and the reef. The reef flat is easily accessible and operations can probably occur nearer the crest along some of the gutters which are mainly rubble/coralline material. At Sandy Bay to the north is a good anchor site if there is a need to keep the boat in the water. Distance from Winderabandi is about 30km north. Water depth is a limiting issue



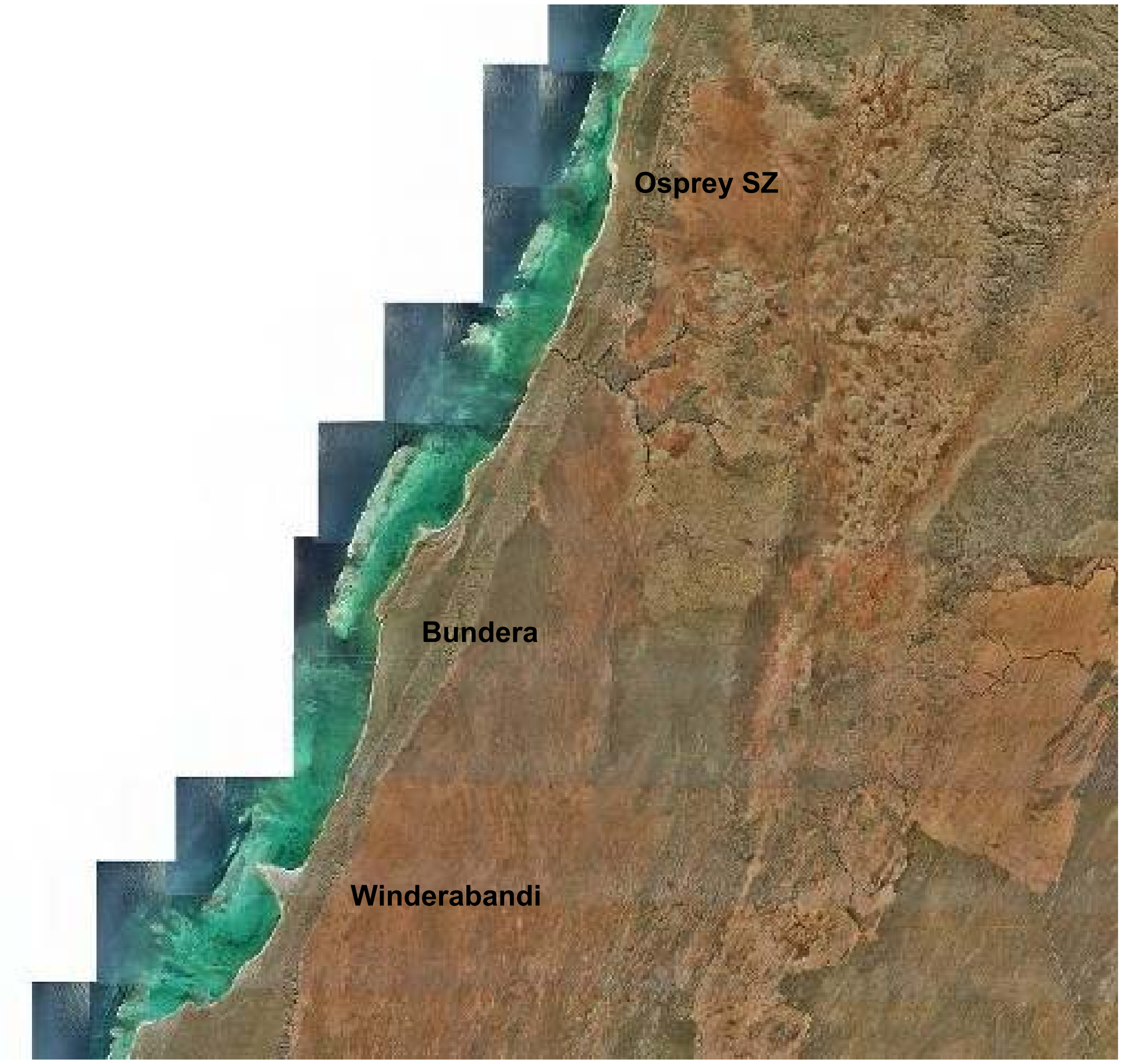
Bundera Campsite

The site is similar to Osprey site with gutters along the reef. There is a campsite and protective lagoon, and an inshore pavement. This site is near Bundera sinkhole and a report of bubbling of water in the lagoon pavement (possible groundwater seep).



All Sites

The relative position of the chosen sites straddles Yardie Creek.



3.2.3. Eastern Reef

A separate but related study has been completed on site test cores taken through the reef system on which the Exmouth marina is now built. This project involved core logging and U-series dating of a transect of diamond drill cores stretching from the shoreline for over 1 km to the east beneath the present day marina navigation channel.

Outcomes of this work on the eastern reef are summarised in this report (Chapter 4) and is published in Marine Geology (Twiggs and Collins, 2010).

3.3. Results

3.3.1. Cores taken, geochronology and growth history

Whilst some results were achieved, coring operations were limited by the significant wave energies experienced throughout the two weeks of fieldwork, such that exposed sites near the reef crest could not be occupied at all, and only some of the reef flat sites in the most protected settings were feasible for safe operations. The equipment was operated under demanding circumstances resulting in some lost operational time as well. Best operating time was around lowest tide, and night operations were excluded, providing further constraints for coring depending on the occurrence times of low tides. As a result coring was attempted at Osprey and Winderabandi only, and in each case the number of holes occupied was decreased along the scheduled transect. A summary of core data collected is given in Table 3.1. Geochronology and sea levels are summarised in Figure. 3.3.

Location	Borehole	Penetration	Recovery	Description	Age (ka)
Winderabandi	W2	0-0.3m	10cm		
	Platform	0.3-0.4m	7cm	Coral Framestone	
	Surface	1.2m	5cm	Coral Framestone, bored	1.209
	0.5m	1.4m	3cm	Coral Framestone	
	Below	1.5m	3cm	*Tumbled Sample*	
	LW	2.1m	4 fragments, 2-3cm	Coral Framestone	
		2.7cm	3cm & 1 tumbled sample	Coral Framestone	
		3.7m	Fragments & 2 at 2-3cm	Coral Framestone, vuggy	
		4.5m	4 fragments at 2-3cm	Coral Framestone	2.573
		4.7m		Coral Framestone, V/C	3.206
Osprey	O2		No recovery	Too sandy, abandoned	
	O3A	3.1m	2 samples 0.7m&0.75m	Poor Recovery	

	O3B	0-1.5m		Sample 3B 1.5m	
		1.5-2.5m		Sample 3B 2.5m	
		1.5-1.6m	10cm continuous	Core dating sample	1.2
		3.5m	4cm segment		3.624
		3.6-3.9m		Rubbly sample	
		3.5-4m		Sandy mud returns	
		4.4-4.5m		Coral Framestone	3.643
		4.5-8m		Cavernous Zone	
		8-8.3m		Rubble recovery, calcretized sample	
		8.3-8.4m		Rubble & core of massive coral framestone	5.472

Table 3.1 – Summary of core data. Depths quoted are core depths. For depths below MSL add 0.5 metres to core depths. For full geochronology and error data see the Core Study Milestone Report

The most successful coring was achieved at Osprey, site O3, where 8.4 metres of Holocene reef was cored from the inner reef flat, and Winderabandi, site W2, where 4.7 metres of Holocene reef was intersected from the secondary reef crest. In both cases full penetration of the Holocene sequence was achieved, providing the potential for isotopic and U-series analysis and dating of the full Holocene sequence in contrasting reef sites. However, core recovery percent was low in both cases. The Last Interglacial reef was penetrated at the base of each hole (subject to confirmation by dating) as predicted based on seismic data from northern Ningaloo Reef (see Collins et al., 2003). However, the core material will provide the first opportunity to obtain data and chronology for Holocene reef growth (in reef flat and near reef crest environments) and response to sea level and palaeotemperature conditions.

The cores were dated by uranium series dating and isotopic analysis at the Centre for Microscopy and Microanalysis at the University of Queensland to assess the growth history objectives. Plate corals and massive corals dominate the Holocene section , but the narrow core diameter limits the coral community information available.

The Pleistocene and Holocene growth history and chronology have been determined for reefs on the western and eastern sides of the Ningaloo Reef. On the western Ningaloo Reef based on reef flat cores at Osprey and Winderabandi the key results are the following:

- The maximum Holocene reef thickness of 8.4 m and the reef has grown to sea-level characterising it as a ‘keep up’ reef.
- Reef growth is significantly later in development than the eastern Ningaloo Reef, where growth terminated at 6.8 ka ago, which is close to the timing of the Late Holocene sea level highstand of +2m along the WA coast.
- Thus active reef flat accretion after the Holocene highstand at Winderabandi and Osprey would have taken place during the slow fall of sea level from about +2m, and this is likely to be a regional occurrence.
- The relationship between reef growth and sea-level fluctuations during the Holocene provides a basis for assessment of the impact of climate and sea-level change on the reef and coastal ecosystems.

There are important contrasts between the Winderabandi site (reef flat, near the reef crest) and the Osprey site (most landward part of the reef flat), particularly in terms of Holocene reef thickness (4.7m at W2; 8.4m at O3). Assuming that both hole bases indicate the elevation of the underlying Last Interglacial reef surface (which is represented by a prominent “step” in the reef wall within a trough immediately seaward of the W2 site, and has also been seismically mapped elsewhere, as well as outcropping in coastal terraces at both sites) the Last Interglacial surface is elevated near the reef crest (at W2) and is deeper to landward at O3, then shallows to become emergent by up to 2m at the coast. Differing reef growth onset ages (=basal dates in cores W2 and O3) would be determined by different drowning ages for this irregular surface as sea level rose during the Late Holocene,

On the eastern Ningaloo Marina Reef (summarised from Twiggs and Collins, 2010; see Chapter 4):

- Maximum Holocene reef thickness is 5 m.
- Reef onset age is 7.9 ka with termination of the reef at 5.8 ka indicating a
- drowned ‘give up’ reef. Distinct reef facies have been identified in the Holocene (MIS1) and Last Interglacial (MIS5e) reef units beneath the Holocene reef.
- Reef development was influenced by antecedent topography, rising sea-levels and changing environmental conditions.
- An underlying marine unit (MIS7?) was identified, deposited during restricted hypersaline marine conditions.

3.4. Discussion

Figure 3.3 summarises all of the offshore Holocene geochronological data recorded from this study (Winderabandi and Osprey lagoon cores; eastern marina reef) and earlier coring at Tantabiddi during previous work at Ningaloo, along with the established reef growth and sea level curve for the leeward Houtman Abrolhos reefs. It should be noted that the chronological information most closely tracking sea level changes comes from reef crest cores (not obtained at western Ningaloo due to energy conditions but available for the Houtman Abrolhos, used here for reference) and that other data will lag behind sea level adjustments, while still providing useful information on reef growth. Also, a fringing reef such as Ningaloo Reef is likely to contain a record of only the latter part of the Holocene sea level history when compared to reefs further offshore (such as the mid-outer shelf Houtman Abrolhos reefs) and may involve interactions with pre-existing topography in the coastal zone.

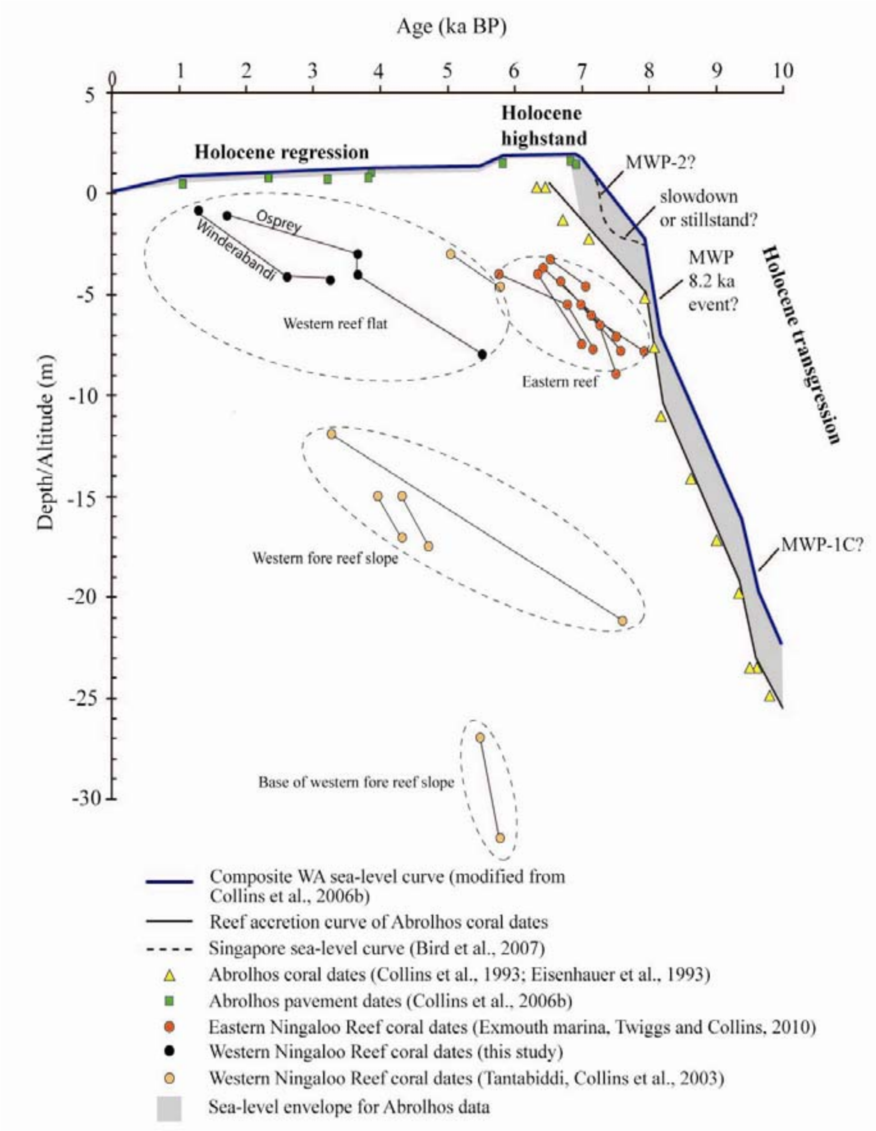


Figure 3.3: Compilation of Ningaloo Reef Holocene geochronology and growth history data, compared with Houtman Abrolhos data corresponding to a "keep up" pattern of reef growth. Blue line represents interpreted sea level curve for the WA coast. Note that reef crest data are not available for Ningaloo Reef.

This compilation allows all the available data to be viewed in context, but it should be emphasised that the information is limited in scope when considering the size and scale of the reef system. Whilst all of the Ningaloo data show significant lags behind the sea level curve, there is good clustering of data within different systems and subenvironments (circled). The eastern (marina) reef most closely approximates the sea level curve, but most growth terminated by the end of the Holocene highstand some 7 ka ago (see discussion in Chapter 4, Twiggs and Collins, 2010). In contrast the western reef grew later by vertical accretion (probably combined with lateral expansion) while sea level fell after the Holocene highstand during regression to present sea level, based on the Osprey and Winderabandi data.

The contrasts between the Winderabandi site (reef flat, near the reef crest) and the Osprey site (most landward part of the reef flat), particularly in terms of Holocene reef thickness (4.7m at W2; 8.4m at O3) reflect the influence of antecedent topography in that the Last Interglacial surface is elevated near the reef crest (at W2) and is deeper to landward at O3, then shallows to become emergent by up to 2m at the coast. Differing reef growth onset ages (=basal dates in cores W2 and O3) reflect different drowning ages for this irregular surface as sea level rose during the Late Holocene, and it seems likely that the position of the western reef crest was controlled by the Last Interglacial reef, similar to the model shown in Fig. 3.2 which was based on previous coring at Tantabiddi (see Collins et al., 2003). Whilst the influence of Last Interglacial reef substrate provided a regional control on Holocene growth along the length of Ningaloo Reef, Pleistocene alluvial fans, built out from the coast near “gorges” such as at Yardie Creek also provided antecedent surfaces for reef colonisation and locally control Holocene reef morphology. In terms of models for fringing reef flat development the western Ningaloo Reef most closely resembles model B (Pleistocene reefal substrate) and model C (Pleistocene alluvial fan substrate) of Hopley and Partain (1987); see also Hopley et al., 2006, Fig.7.7 for details of these models.

Following reef flat accretion to close to present levels and sea level stabilisation energy regimes across the reef flat would have also stabilised, leading to the modern reef community which most likely reflects those conditions.

3.4.1. Conclusions

The limited coring carried out on the western reef during the project demonstrated the feasibility of obtaining shallow cores from the reef flat using low cost, lightweight portable drilling equipment whilst underlining the difficulty and weather dependence of gaining the data. Nevertheless there are severe limitations on operating sites and length and quality of core recovery compared to the more robust and expensive drilling equipment used in conventional full-scale geological reef studies. Core analysis (U-series dating) addressed the objectives of:

- The relationship between the Last Interglacial and Holocene reefs
- The sea level and growth history of the Holocene (last 10,000 years) as determined from U-series dating
- The chronology of reef growth onset, duration and termination
- The response of the reef system to past Holocene sea level rise, and the likely response to future sea level change.

Whereas little was previously known about the timing of Holocene reef growth, the chronological framework developed shows the contrasting pattern of eastern and western reef development, and the persistence of western reef flat growth into the late Holocene. The importance of antecedent topography and the control exerted by the Last Interglacial phase of reef growth over modern reef morphology have been confirmed by the coring results.

The related study of site test cores taken through shallow reef environments seaward of the Exmouth marina within Exmouth Gulf yielded high quality information on the growth history of the eastern reef (see Chapter 4, Twiggs and Collins, 2010).

Overall, limited but significant information has been gained about reef structure and growth history, as summarised in this report. However, scope remains for a full scale geological assessment of the whole reef tract as opposed to the limited and highly targeted research that could be completed within the scope and budget for the growth history component of WAMSI Project 3.4.

The issue of the climate change future of Ningaloo Reef is of significance for marine park (and potential World Heritage) management of the reef system. The key issues for reef systems are likely to be coral bleaching, increased storminess, increased sea level and ocean acidification. These topics are discussed in general in Chapter 4 and Twiggs and Collins (2010) and in relation to the eastern Ningaloo reefs in particular.

Hopley et al., (2006) highlight the following future impacts for coral reefs:

- An increase in average temperature, of between 0.4 and 2.0 C by 2030 and of between 1.0 and 6.0 C by 2080;
- More periods of extreme heat;
- More frequent El Nino-Southern Oscillation (ENSO) events;
- Rainfall increases across much of the tropical north;

- More severe wind speeds in cyclones and associated storm surges being progressively amplified; and
- A possible change in ocean currents affecting coastal waters.

A recent authoritative statement on likely future impacts for coral reefs produced in 2009 by a working group led by J.E.N. Veron is as follows:

The Coral Reef Crisis: scientific justification for critical CO_2 threshold levels of < 350ppm

Output of the technical working group meeting. The Royal Society, London, 6th July 2009

> 'The issue of rising sea levels (by as much as 1 meter by 2100, based on most recent projections) will have important impacts on the reef and coast, such as changing hydrodynamic conditions at the reef crest and in the lagoon, and erosion al retreat of sandy coasts by up to 100m.'

In section 2 (key findings) a series of management oriented issues are addressed and it is anticipated that the matters discussed will serve as a reminder that reef geomorphology and growth history are of fundamental importance to management considerations especially as climate change questions will continue to emerge in the future. Such assessments will need to consider the structure and past evolutionary history of the reef system.

3.5. Acknowledgements

This research was funded by the Western Australian Marine Science Institute (WAMSI). The project is being undertaken as part of WAMSI 3.4. Coring equipment for the study was provided by Dr Bradley Opdyke of the Australian National University. Dr Opdyke and Ms Merinda Naish of ANU carried out the coring operation (with Matthew Snow and Lindsay Collins of Curtin).Special thanks are due to the coring team for their efforts under challenging operating conditions. Dr Jian-xin Zhao of the University of Queensland is thanked for provision of U-series dates for the core studies. Thanks are also due to the DEC (Exmouth Office) for assistance with field accommodation and Dr Glen Whisson (Curtin) for small boat assistance. Ms Emily Twiggs (Curtin) provided reef reconnaissance advice for operations.

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4. Reef Geomorphology and Growth History – Eastern Ningaloo Reef

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Abstract

Reefs lining the western Exmouth Gulf, located at the northern limit of the 300 km long Ningaloo Reef in Western Australia, represent modern incipient coral reefs and veneers of non-reef-building coral/algal communities on exposed Pleistocene or 'give-up' Holocene reef surfaces. Acquisition of sixteen cores alongside U-series TIMS dates were used to confirm the nature of the Pleistocene foundation and characterise Holocene reef development. Three calcretised Pleistocene units were identified as 1) the Last Interglacial (MIS 5e) reef directly underlying Holocene units, 2) a mid-Pleistocene (MIS 7?) bioclastic conglomerate unit, and 3) a Pleistocene alluvial fanglomerate. Eight Holocene reef facies (total thickness of 1.8–5.3 m) included coral framework facies (domal, arborescent, mixed, tabulate and encrusting) and detrital facies (carbonate sand, skeletal rubble and alluvial fan deposits). Holocene ages range from 7.93 to 5.8 ka BP with vertical accretion ranging from 1.46 to 9.88 mm/year (avg. 4.11 mm/year). Highest rates of accretion and thickest accumulation occurred in the most seaward and deepest cores composed of massive coral framestone and coralline algal crusts.

A six stage Holocene chronology is proposed, including 1) coastal inundation from 8 to 8.5 ka BP, 2) initiation 'start-up' from 8 to 7.5 ka BP, 3) rapid growth 'catch-up' and back-step from 7.5 to 7 ka BP, 4) rapid aggradational growth 'catch-up' from 7 to 6.5 ka BP, 5) reef decline 'give-up' and detrital buildup from 6.5 to 5.8 ka BP, and 6) detrital buildup and progradation from 5.8 ka BP to present. Changes in reef facies and the ultimate demise of the Holocene reef probably involved a combination of increased sea-level, coastal flooding and erosion during the mid-Holocene highstand, with associated increase in sedimentation, turbidity and decline in water quality; burial by sediment buildup during the mid-Holocene highstand and detrital progradation during the mid- to late-Holocene regression; and, the introduction of alluvial sediment during cyclones and other severe storms to an already stressed community. Modern communities have thus shifted from coral-dominated to bored macroalgal pavements. This study shows that integration of reef development processes with response to environmental change can be used to assess future pressures on coral reef ecosystems globally.

4.1. Introduction

Climate change and its detrimental effect on coral reefs has been widely reported (Hoegh-Guldberg, 1999; Hughes et al., 2003; Hallock, 2005; Hoegh-Guldberg, 2006; Hoegh-Guldberg et al., 2007; Wilkinson, 2008). Major environmental change and associated reef response may include increased sea surface temperatures resulting in coral bleaching, disease and mortality (Hoegh-Guldberg, 1999; Walther et al., 2002; Hoegh-Guldberg et al., 2007; Baker et al., 2008), increased bioerosion (Smithers et al., 2007), and ecological range shifts (Precht and Aronson, 2004; Greenstein and Pandolfi, 2008); rising ocean acidification slowing coral calcification and reef growth (Kleypas et al., 2001; Raven et al., 2005; Kleypas et al., 2006; Hoegh-Guldberg et al., 2007; Fabricius, 2008; Veron, 2008; Wei et al., 2009); rapidly rising sea-level with slower growth of deeper corals or reef 'drowning' (Smithers et al., 2007), loss of coastal protection (Hoegh-Guldberg, 2006) and shoreline flooding with increased sedimentation and decreasing water quality (Smithers et al., 2007); and increased severe storms and cyclones with the physical destruction of corals, modification of communities, increased erosion and sediment transportation (Smithers et al., 2007). Environmental changes are likely to act synergistically to reduce coral populations having dramatic consequences for coastal biodiversity, protection and socio-economic implications (Hoegh-Guldberg, 2006). Some reefs may adapt with strategies such as reef flat reactivation (Hopley, 1996; Hopley et al., 2007) and back-stepping of corals to shallower substrates during rapid sea-level rise (Smithers et al., 2007; O'Leary et al., 2008; Blanchon et al., 2009). Fringing and nearshore reefs commonly occur in conditions already considered marginal for reef growth (Perry, 2003) and their long-term prospects during climate change and other anthropogenic activities are considered poor (Smithers et al., 2006).

Predicting how reefs may respond to environmental change is difficult due to the lack of long-term ecological data (Pandolfi and Greenstein, 2007). Consequently the fossil record provides us with an insight into the nature and rates of past change, which is increasingly relevant for assessing future coral reef response (Blanchon and Montaggioni, 2003; Precht and Aronson, 2004; Smithers et al., 2006; Pandolfi and Greenstein, 2007; Smithers et al., 2007; Greenstein and Pandolfi, 2008).

Reef development since the Last Glacial Maximum (LGM, ~20 ka, ka=1000 years) and particularly during the Holocene (last 10 ka) has seen reefs respond in a number of ways to environmental change, including modifications of reef assemblages (Montaggioni, 2005), 'turn-on' or 'turn-off' of reef building communities (Buddemeier and Hopley, 1988), and 'catch-up' or 'keep-up' growth strategies in response to sea-level (Davies and Hopley, 1983; Neumann and Macintyre, 1985). Reef cessation records the biological and geological responses of coral reefs that 'give-up' and 'turn-off' carbonate production (Neumann and Macintyre, 1985; Buddemeier and Hopley, 1988), and a number of contributing factors have been identified including burial by sediments, turbidity, lower irradiance, excess nutrients, changes in seawater chemistry and drowning as a result of rapid sea-level rise during the postglacial transgression (Montaggioni, 2000; Kleypas et al., 2001; Montaggioni, 2005; Beaman et al., 2008; Harris et al., 2008).

Western Australia (WA) has been described as perhaps the best natural laboratory for studying the effect of climate change on shallow-water carbonates (Hallock, 2005). Modern and late-Pleistocene coral reef communities exposed along the Cape Range region in northwest WA, provide a unique example in which to investigate the impact of climate change on coral reefs (Greenstein and Pandolfi, 2008). In this study we present reef core data and U-series TIMS dates to provide an insight into the Holocene evolution of the eastern Ningaloo Reef within the Exmouth Gulf embayment. The objectives of this research were to 1) determine the nature of the pre-Holocene foundation and its influence on Holocene development, 2) establish Holocene reef development and biofacies relationships, and 3) produce a chronology of Holocene development during environmental change. This information allows us to explore the processes that contributed to the evolution and ultimate demise of a section of the eastern Ningaloo Reef, providing an analogue for the assessment of environmental change on coral reefs globally.

4.2. Regional setting

4.2.1. Biogeographic setting

Ningaloo Reef is a 300 km long fringing to barrier reef in WA, from Red Bluff in the south to the northwestern Exmouth Gulf in the north (Fig. 4.1A). The Ningaloo Reef occurs in a transitional biotic zone resulting in diverse marine assemblages (Collins et al., 2003), and along with the Cape Range has been nominated for World Heritage Listing due to its outstanding natural significance (www.unesco.org).

4.2.2. Geological setting

Exmouth Gulf is situated east of the North West Cape (Fig. 4.1A, B) and is a large (~3000 km2) subtropical, strongly tidal and inverse estuarine embayment. It is 21 m at its deepest and has a relatively narrow entrance with a small sill in depths of ~19 m. It is flanked on the west by the deeply dissected and uplifted Cape Range anticline consisting of exposed Miocene subtropical continental shelf carbonates of the Cape Range Group (Hocking et al., 1987; Apthorpe, 1988; Collins et al., 2006a) which strongly control the regional hydrogeology (Lee, 2008). Tertiary sequences are overlain by four Pliocene–Pleistocene terraces and raised reefs (Van de Graff et al., 1976; Wyrwoll et al., 1993). The lower Tantabiddi Terrace lacks deformation, attesting to the tectonic stability of this 'farfield' region since the Last Interglacial (Wyrwoll et al., 1993; Collins et al., 2003). It comprises extensive coralgal reef deposits occurring as subtidal–intertidal

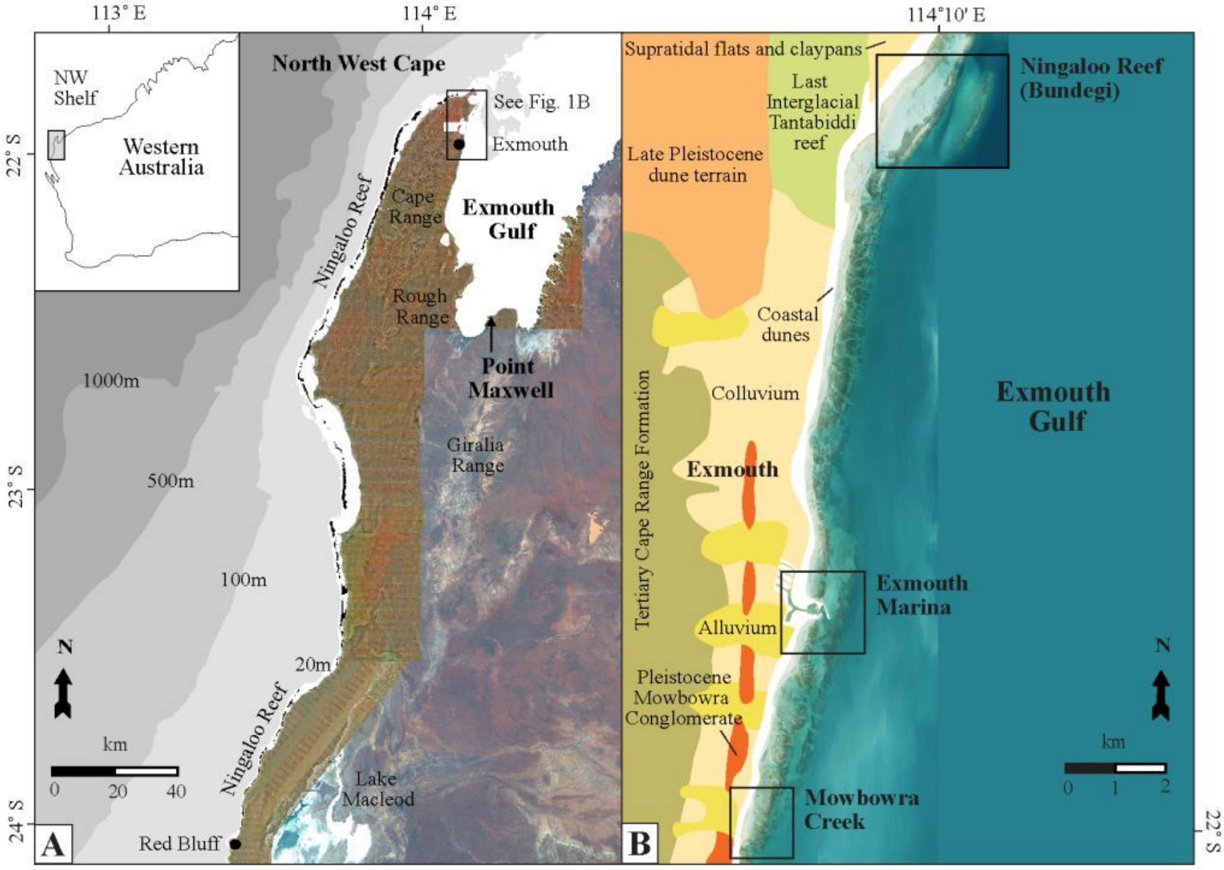

Figure. 4.1. Location maps showing (A) WA and the North West Cape region, also study site at Point Maxwell in the southern Exmouth Gulf, and (B) northwest Exmouth Gulf and study sites including Bundegi Reef, Exmouth marina core site and Mowbowra Creek. See Fig. 2 for additional detail.

pavements, emergent coastal platforms, and as the foundation beneath the contemporary Holocene reef (Collins et al., 2003). The Tantabiddi is of Last Interglacial Marine Isotope Stage (MIS) 5e with U-series dates obtained from the west side of the Cape Range (Kendrick et al., 1991; Stirling et al., 1998; Collins et al., 2003; Hearty et al., 2007).

The Exmouth area lies on a coastal plain formed by colluvium and alluvium and includes extensive outcrops of the Mowbowra Conglomerate with its type section located along Mowbowra Creek (Fig. 4.1B). On the western Ningaloo Reef, Holocene reef growth veneered the Tantabiddi reef near its submerged seaward margin and formed a relatively thin unit of ~10–15 m below the reef crest (Collins et al., 2003). The western reef occurs in open-ocean conditions and has distinct geomorphic zonation with a well developed and wide (~150 m) reef flat (Collins et al., 2003; Cassata and Collins, 2008). As the reef wraps around the North West Cape into the more turbid and lower energy conditions of the Exmouth Gulf embayment, it becomes increasingly submerged and closer to shore with little reef flat development.

Surface soils of the Exmouth Gulf coastal plain are highly weathered residues of red, iron-rich aluminosilicate minerals (Brunskill et al., 2001). In the northwest Gulf, sediments are mixtures of medium-coarse carbonate sand, red–brown iron-stained quartzose fine sand, relict coralline and shell gravel, and limestone lithoclasts (Brown 1988; Orpin et al., 1999; Brunskill et al., 2001). Major factors that control sediment distribution are the impact of cyclones bringing an influx of red siliciclastic sediment from the hinterland, bottom sediment resuspension and transport by wind waves and strong tidal currents, and within the last 30 years sediment disturbance caused by commercial prawn trawling (Orpin et al., 1999).

4.2.3. Climate and oceanography

The North West Cape region is arid with hot summers (22.9–38.1 °C) and mild winters (11.4–24.2 °C), under low rainfall (~260 mm/year) and high evaporative conditions (1700–3050 mm/year) (Bureau of Meteorology 1975–2009 records, www.bom.gov.au). Exmouth Gulf is influenced by a high pressure subtropical ridge to the south and a trough of low pressure during the summer, producing general south to southeasterly winds for much of the year. Cyclones (N90 km/h) occur once every 2–3 years (Australian Bureau of Meteorology, www.bom.gov.au) with the semi-enclosed waters of the Gulf forming damaging storm surges. These catastrophic events cause widespread flooding and erosion to the coastline, and high turbidity conditions (McIlwain, 2002). Cyclones are responsible for 20–40% of the annual freshwater input into the Gulf through alluvial channels and this activity may have been similar for the last 6 ka (Wyrwoll et al., 1993).

Exmouth Gulf has mixed semi-diurnal tides with a mean spring tide of 1.8 m (APASA, 2005). The Gulf waters are protected from the open-ocean swell by the North West Cape and islands that line the entrance. Local wind-generated waves (to ~1.5 m) dominate the northern parts of the Gulf (Oceanica Consulting Pty Ltd, 2006) and circulation is forced mainly by tidal currents orientated north–south along the western margin (Massel et al., 1997; APASA, 2005). Sea surface temperatures range from 22 to 28 °C and the regional oceanography is dominated by the Leeuwin Current, a coastal boundary current carrying warm, low salinity, low-nutrient water poleward along the adjacent shelf slope to shelf break (Smith et al., 1991), flowing strongest during autumn–winter and La Nina years (Feng et al., 2003). The Gulf is in close proximity to the Leeuwin Current and consistently affected by warm water during the summer. This is in contrast to the western side of the North West Cape which is affected in the summer by the Ningaloo Current, a wind-driven equatorial surface current on the continental shelf which drives upwelling on the shelf slope (Hanson et al., 2005).

4.3. Materials and Methods

4.3.1. Contemporary geomorphology

Contemporary reef and coastal geomorphology were investigated using hyperspectral remote sensing data collected by HyVista Corporation. Bathymetry was determined using extracted water depths from hyperspectral imagery provided by the Remote Sensing and Satellite Research Group (RSSRG) at Curtin University of Technology using methods of Klonowski et al. (2007). Hyperspectral imagery was draped over bathymetry using Global Mapper v10 software (www.globalmapper.com). Modern reef communities were not described at the marina core site due to disturbance by dredging. The Ningaloo Reef at Bundegi (Fig. 4.1B) is a continuous reef deemed suitable as a local modern analogue and an understanding of modern reef communities was determined during a qualitative snorkelling survey in 2007.

4.3.2. Reef coring

Coring was undertaken during a geotechnical investigation of the Exmouth marina site (Fig. 4.1B) in 1995 for the Department for Planning and Infrastructure (DPI) (Soil and Rock Engineering, 1995). To determine an overall picture of reef development 16 cores were chosen along a shore-normal transect (Fig. 4.2A). Cores were obtained using a diver-operated submersible drilling rig using water flush and rotary coring techniques. The drilling was carried out using both HQ and HQ3 size cores barrels with core lengths between 3.5 and 6 m. Topographic positions were corrected to mean sea-level (MSL) for comparison with palaeo sea-level data.

4.3.3. Core description and sampling

Cores were logged for stratigraphy of major reef units including sediment/rock types, boundaries and hiatuses; primary, secondary and associated reef builders; and other physical features such as calcrete horizons and borings. Sediment/rock types were classified according to the expanded carbonate classification of Dunham (Dunham, 1962; Embry and Klovan, 1971) and the textural scheme of Udden–Wentworth (Udden, 1914; Wentworth, 1922). Bio-lithofacies were described according to the growth form of primary framework builders and non-framework detritus using a modified scheme of Montaggioni (2005), and fossil corals were identified to genus level where possible.

4.3.4. U/Th coral dating

Seventeen coral samples were selected for dating by high precision U-series thermal ionization mass spectrometry (TIMS) at the University of Queensland (UQ) using analytical procedures described in Zhao et al. (2001) and Yu et al. (2006). The Thompson U-series open-system model was used for Pleistocene corals that had undergone diagenetic alteration (Thompson et al., 2003). These dates have lower precision and are model-dependant but useful when used in a stratigraphic context. Two dates for samples from Point Maxwell in the southern Exmouth Gulf (Fig. 4.1A) were included to support Last Interglacial dates from published data. All dates are given in ka BP.

4.3.5. Accretion rates

Reef accretion rates are defined as a positive balance between constructive and destructive processes (Gherardi and Bosence, 2005). Vertical accretion rates were obtained using U-series dated material in relation to the thickness of the deposited carbonates (i.e. in-situ coral framework and detrital units) and measured in vertical direction of accretion expressed as mm/year (Montaggioni, 2005). Calculated accretion rates represent only an approximate value due to the potential of the original depositional fabric being disturbed during reworking and displacement (Davies, 1983) and artefacts of coring (Blanchon and Blakeway, 2003).

4.4. Results

4.4.1. Contemporary reef and coastal geomorphology

The Ningaloo Reef within the Exmouth Gulf becomes increasingly incipient where it is best described as a submerged reef that lacks a defined reef flat (Hopley et al., 1989; Smithers et al., 2006). This morphology appears to be in part related to a marked change in oceanographic conditions and an increase in turbidity in the Gulf, which can affect coral community composition and ultimately carbonate accumulation (Hallock and Schlager, 1986). The reef and coastal geomorphology at Bundegi, Exmouth marina and Mowbowra Creek are illustrated in Fig. 4.2B–D alongside photographs in Fig. 4.3, and described below.

At Bundegi (Fig. 4.2B) there are distinct multiple reefs comprising a nearshore reef in depths of ~5–10 m, a shallow inshore reef in ~2–5 m and a shoreline intertidal–subtidal pavement. Data is limited on the deeper nearshore reef but hard coral growth is patchy and communities include deeper-water filter feeders such as soft corals, gorgonians, sea whips, sponges and bryozoans. Coral reef communities are prolific on the shallow inshore reef and include thickets of arborescent and caespitose *Acropora* and *Pocillopora*, and associated encrusting to foliose *Montipora* (Fig. 4.3A); mixed communities with arborescent, large tabulate *Acropora* (*Acropora spicifera* and *Acropora hyacinthus*), small corymbose *Acropora* (*Acropora valida, Acropora digitifera*, and *Acropora nasuta*), minor encrusting to foliose *Montipora*, small domal Favids (*Favites* and *Favia*), and submassive *Millepora* (Fig. 4.3B); and communities dominated by tabulate and corymbose *Acropora* (Fig. 4.3C). Massive *Porites* coral 'bommies' are common on the seaward edge of the reef in depths of ~4–6 m. The shoreline limestone pavement has a thin veneer of gravelly carbonate sand and is dominated by macroalgae (mainly *Sargassum*, *Padina*, *Halimeda* and *Dictyota*) and turf algae with minor corymbose and tabulate *Acropora* and domal Favid corals. During Cyclone Vance in 1999, a 3.6 m storm surge in the Gulf smothered corals with increased

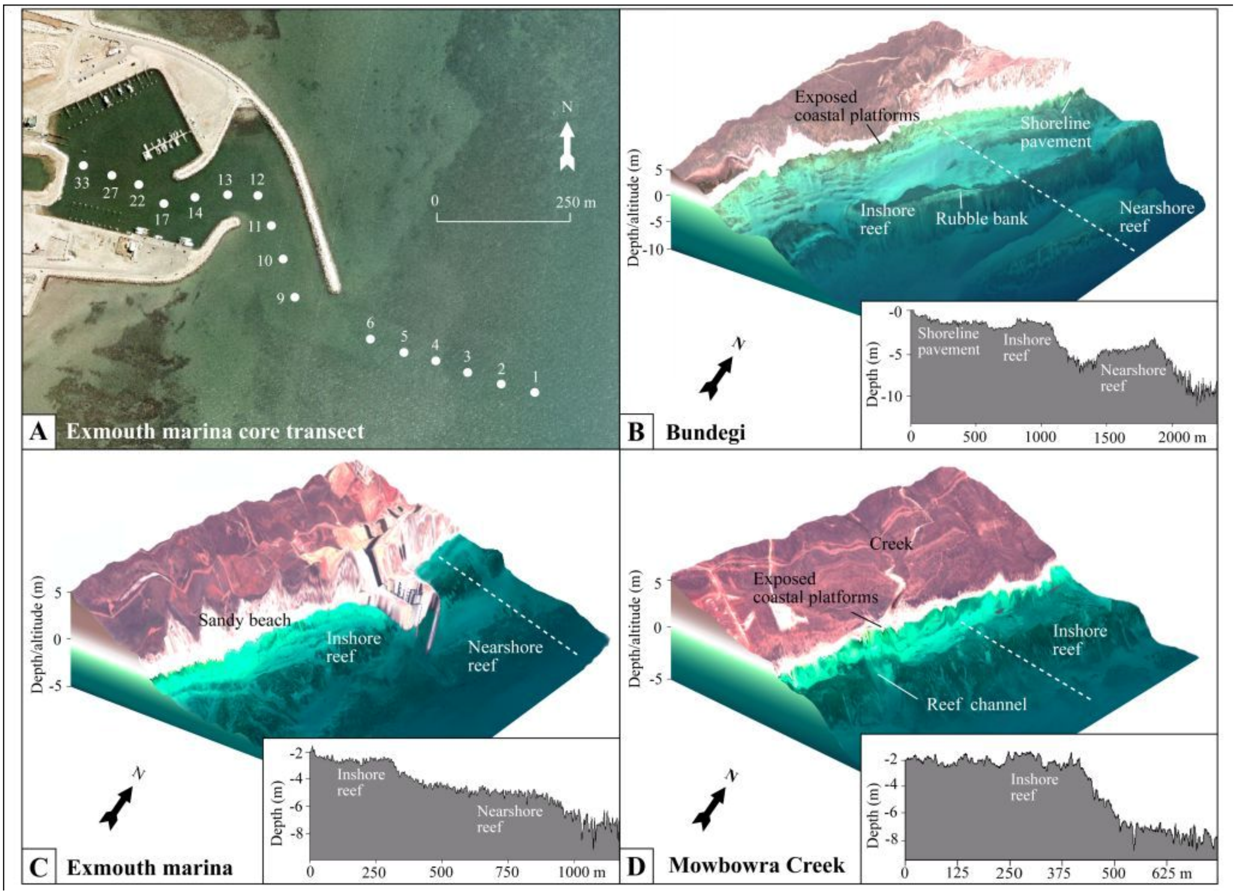

Figure. 4.2. (A) Exmouth marina site showing sixteen core locations (MBH1–33). Geomorphic environments and bathymetric transects are shown for (B) Bundegi, (C) Exmouth marina and (D) Mowbowra Creek. For site locations see Fig. 4.1B.

sedimentation and turbidity and physically destroyed the framework creating distinct rubble banks largely of arborescent coral fragments (Fig. 4.3D). The reef continues south to Exmouth marina, incised by numerous channels which have formed as a result of ephemeral creeks bringing freshwater and alluvial sediments into the Gulf (Fig. 4.1B).

At Exmouth marina core site (Fig. 4.2A, C) the reef surface is dominated by macro and turf algae with minor corals (Fig. 4.3E). The main carbonate secreting organisms include articulated red coralline algae, molluscs and foraminifera with minor *Halimeda*, bryozoans, and echinoids. The reef consists of a shallow inshore reef pavement in depths ~2–4 m and a nearshore reef at ~5–8 m (continuous with the reefs at Bundegi), separated by gravelly sand veneers.

South of the core site at Mowbowra Creek (Fig. 4.2D) the coastline is composed of Last Interglacial Tantabiddi reef occurring as highly bored shoreline algal pavements and emergent, wave-cut platforms at elevations of approximately 1.5 m. The inclined Mowbowra Conglomerate and alluvial fanglomerates are commonly interbedded with the Tantabiddi (Fig. 4.3F, G). At Point

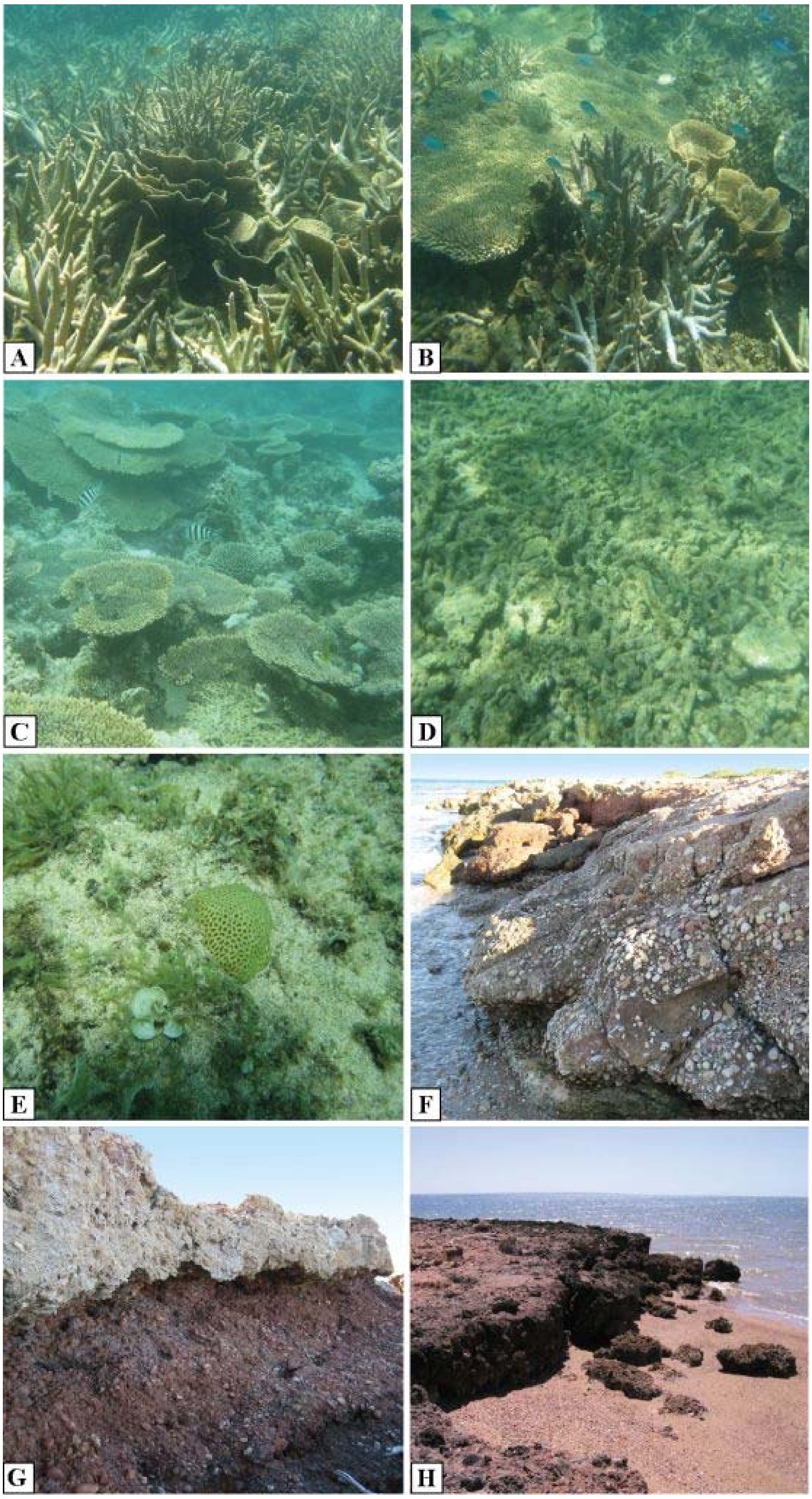

Figure. 4.3. Contemporary communities and coastal geomorphology, Exmouth Gulf, WA. A–E: foreground width of field ~1 m. (A) Arborescent and caespitose *Acropora* thickets with associated foliose *Montipora*, Bundegi inner reef. (B) Mixed tabulate and arborescent *Acropora* and foliose *Montipora*, Bundegi inner reef. (C) Tabulate and corymbose *Acropora*, Bundegi inner reef. (D) Arborescent-dominated coral rubble, Bundegi rubble bank. (E) Algal-dominated pavement with minor coral (*Favites*), Exmouth marina. (F) Inclined foreset of Mowbowra Conglomerate in foreground and Last Interglacial (MIS 5e) Tantabiddi reef platform in background, Mowbowra Creek, height of section ~1.5 m above MSL. (G) Mowbowra Conglomerate overlain by Tantabiddi reef deposits, Mowbowra Creek, ~1.5 m height. (H) Exposed Tantabiddi reef platform, Point Maxwell looking north to Exmouth Gulf, ~1.5 m height.

Maxwell in the southern Exmouth Gulf, there is a wave-cut, highly bored, lower platform of Tantabiddi reef at ~1.5 m with well preserved, in-situ corals (Fig. 4.3H) and an upper platform at ~2 m (described by Greenstein et al., 2005).

4.4.2. Stratigraphy and lithofacies

Stratigraphic core data revealed distinct lithofacies including both Holocene and underlying Pleistocene units (Figs. 4.4 and 4.5).

Holocene unit

Domal coral facies (Fig. 4.5A).

This facies dominates the Holocene reef framework forming buildups of up to 4 m. It includes dome shaped poritids (*Porites*, *Goniopora*), faviids (*Favia*, *Favites*, *Platygyra* and *Plesiastrea*) and mussids (*Symphyllia*, *Acanthastrea*). Subordinate forms include Oculinids (*Galaxea*) and minor tabulate *Acropora* corals. It is generally highly bored by bivalves (*Lithophaga*) and polychaetes. Two subfacies which can be differentiated from the degree of associated coralline algal crusts (as identified by Montaggioni, 2005). Massive corals encrusted with coralline algal crusts (1–10 cm thick) are found in seaward cores associated with minor encrusting bryozoans and surpulid polychaetes, and rhodoliths (b2 cm) in a matrix of reef detritus. Thin or non-encrusted subfacies are present in leeward cores commonly filled with red/brown alluvial mud within corallites, borings and cavities. This facies is typical of low energy reef settings formed in semi-exposed to sheltered paleoenvironments from surface to moderate depths of ~10–15 m (Montaggioni, 2005). Modern domal coral communities at Bundegi reef include large *Porites* corals in depths of ~4–6 m.

Arborescent coral facies (Fig. 4.5B).

Arborescent corals are common throughout the Holocene framework forming buildups of up to 2 m predominantly in leeward cores, consisting of partially lithified, upright thin-branched (~20 cm diameter) interlocking corals and fresh fragments. Corals are dominated by arborescent pocilloporids (*Pocillopora*) and acroporids (*Acropora*). They are commonly associated with domal *Porites* and faviids (*Goniastrea*, *Favites*), and minor tabulate *Acropora*. Corals are frequently bound by thin crusts of red coralline algae. This facies is also characterised by extensive bioerosion primarily by *Lithophaga*. Unconsolidated to poorly cemented bioclastic sand is present in cavities and borings composed of coral, molluscan, articulated and encrusting red coralline algal debris, and foraminifera including *Amphisorus*. Fine alluvial sand is also common composed of calcretised Pleistocene and Tertiary grains. This facies is generally typical of reef growth in sheltered settings at paleodepths of 0–20 m (Montaggioni, 2005). Modern arborescent *Acropora* and *Pocillopora* communities at Bundegi occur on sheltered, inner reef settings in shallow depths of ~2–5m.

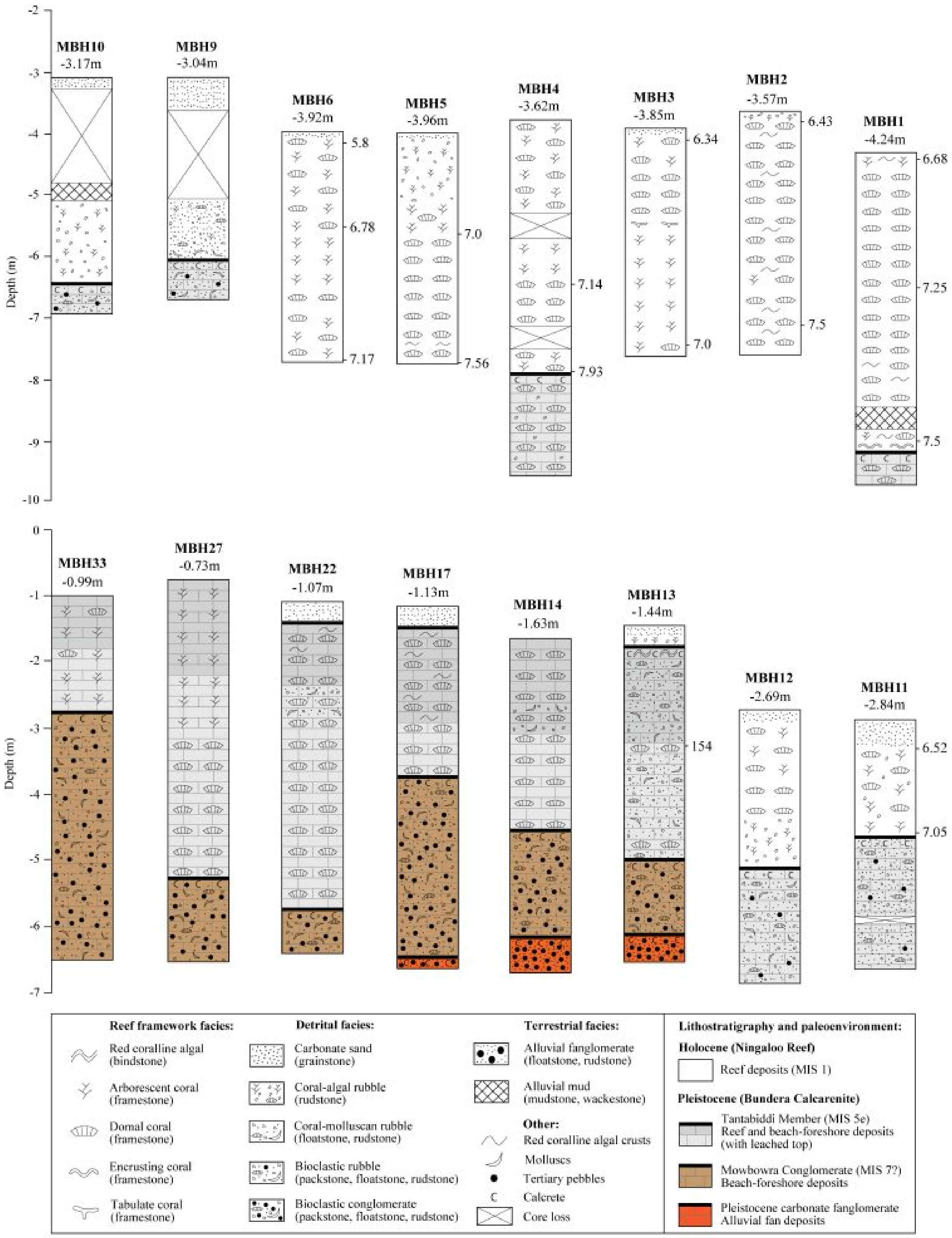

Figure 4.4. Detailed core logs from Exmouth marina transect showing lithostratigraphy and paleoenvironment, lithofacies, and relationships between Holocene and Pleistocene units. Dates are in ka BP and are based on U-series TIMS dating (refer to Table 4.1). For core locations see Fig. 4.2A. Depth of the top of core is given alongside core label and is relative to MSL.

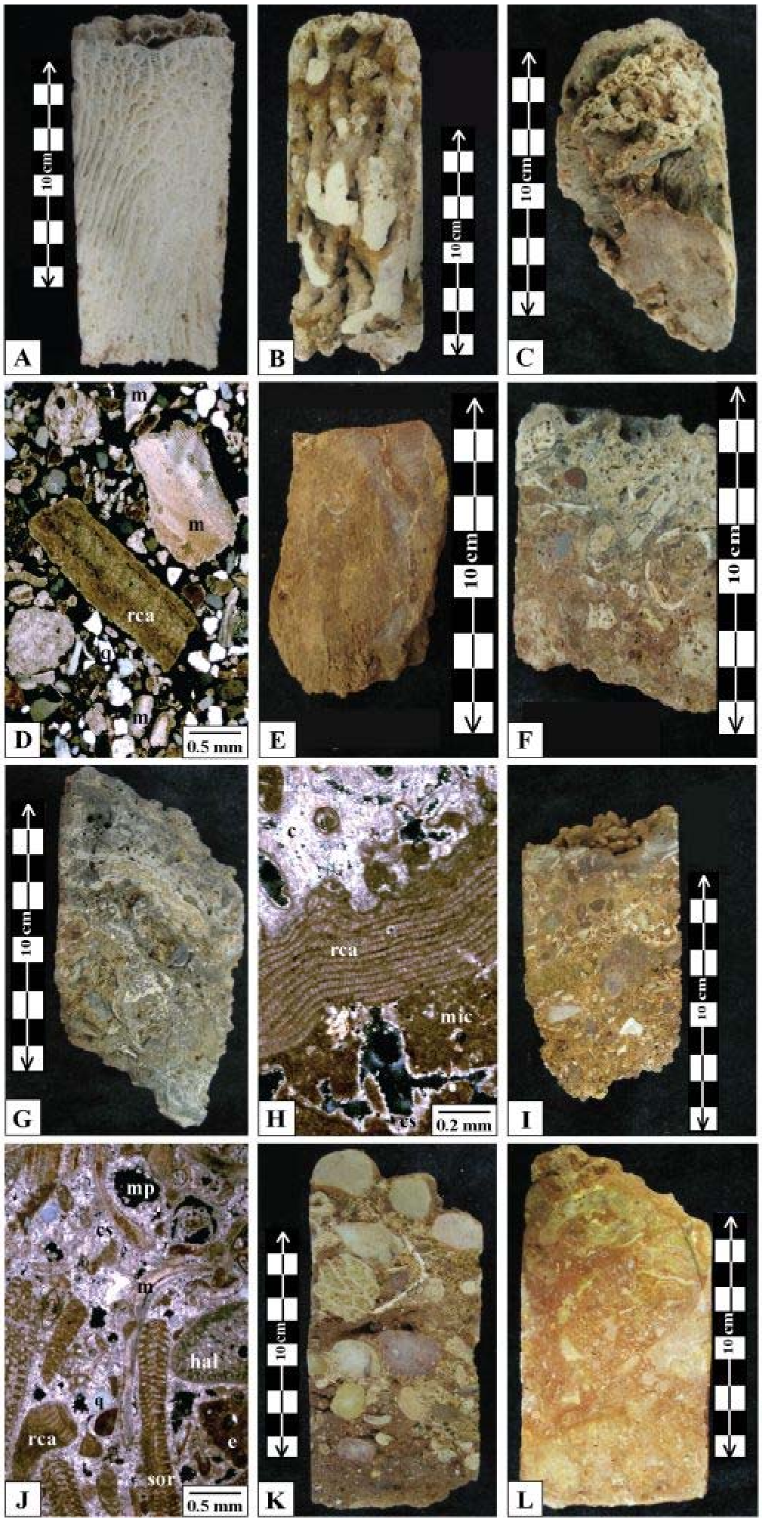

Figure. 4.5. Core photographs showing selected Holocene and Pleistocene lithofacies, Exmouth marina, WA. (A) Domal coral framework facies (*Platygyra*), Holocene. (B) Arborescent coral framework facies (*Pocillopora*), Holocene. (C) Encrusting coral framework (*Montipora*), Holocene. (D) Photomicrograph of carbonate sand facies, Holocene, with molluscs (m), red coralline algae (rca) and quartz (q). (E) Alluvial mud facies, Holocene. (F) Highly bored Tantabiddi surface, Last Interglacial. (G) Algal bindstone facies, Last Interglacial. (H) Photomicrograph of algal bindstone facies, with coral (c), red coralline algae (rca) and micritic matrix (mic) with replacement by calcitic sparite (cs). (I) Bioclastic rubble facies, Last Interglacial. (J) Photomicrograph of bioclastic rubble facies, with molluscs (m), soritid foraminifera (sor) (*Amphisorus*), *Halimeda* (hal), extraclasts (e), quartz (q), calcitic sparite matrix (cs) and moldic porosity (mp). (K) Bioclastic conglomerate facies, Pleistocene. (L) Alluvial fanglomerate facies, Pleistocene.

Mixed domal/arborescent coral facies.

A mixed facies has been defined in cores with both arborescent and massive forms that cannot be separated into individual facies. Buildups of up to ~1.5 m occur, predominantly at the base and tops of leeward cores. Dominant corals include acroporids (*Acropora* and *Astreopora*) and domal *Porites*, faviids (*Plesiastrea*, *Cyphastrea* and *Favites*) and mussids (*Lobophyllia*). Minor encrusting *Montipora* is also present as overgrowths on arborescent *Acropora* fragments.

Tabulate coral facies.

This facies is up to 0.2 m thick and consists of tabulate *Acropora*. It was only encountered in a one core (MBH3) separating arborescent and domal coral facies. Tabulate facies occur in a wide variety of settings in the Indo-Pacific paleo-record and is thought to represent moderate wave energy at depths not exceeding 15 m (Montaggioni, 2005). At Bundegi reef tabulate corals dominated by *Acropora*, including *A. spicifera* and *A. hyacinthus*, are present in shallow depths of ~2–4 m.

Encrusting coral facies (Fig. 4.5C).

Encountered in the Holocene basal section of core MBH1 with 0.2 m thickness, this facies consists of lamellar encrusting coral framestone of *Montipora* associated with small domal Oculinidae (*Galaxea*). The principal framework also includes highly bored, laminar encrusting red coralline algae. Interstices are infilled with alluvial mud and bioclastic sand. Modern counterparts of this facies have been observed in a variety of reef environments subject to low light levels. Facies rich in terrigenous mud are considered to have formed in protected environments in less than 10 m depth (Montaggioni, 2005).

Carbonate sand facies (Fig. 4.5D).

Unconsolidated to partially lithified skeletal grainstone to packstone occurs throughout the Holocene unit infilling interstices in the framework, borings and corallites. Extensive deposits occur in leeward cores, in particular MBH9 and 10, and as veneers over the Holocene framework. Sediments are poorly sorted and composed of a mixture of coarsemedium bioclastic sand, coralline algae and shell gravel, subangular to subrounded iron-stained quartzose grains and calcretised Tertiary and Pleistocene extraclasts. Skeletal sand and gravels are bioeroded, heavily abraded and relict in appearance. Components are dominated by molluscs, foraminifera (porcellaneous, hyaline and agglutinated groups), articulated and encrusting red coralline algae and corals, with minor echinoderms, *Halimeda* and bryozoans. Extraclasts have been introduced from the erosion of wave-cut Pleistocene coastal platforms and alluvial sediments as suggested by Brown (1988). The quartz component is thought to represent aeolian-derived sediment (Orpin et al., 1999) transported by wind and fluvial delivery during flood events.

Skeletal rubble facies.

Two types of skeletal rubble occur within the cores. The first is an abraded coral shingle facies comprising arborescent forms encrusted by red algae. This facies is up to 1.5 m thick occurring in leeward cores. The second type contains coral–molluscan rudstone to floatstone up to 1 m thick in leeward cores.

Alluvial mud facies (Fig. 4.5E).

Distal alluvial mud occurs in two Holocene cores (MBH1 and 10) forming ~20 cm thick beds. It is a well lithified wackestone with fine-medium sized grains in a red/brown muddy matrix. Grains include subangular Pleistocene extraclasts, angular–subangular quartz grains, subrounded relict fragments of articulated red coralline algae, molluscs, and milliolid and rotalinid foraminifera. The matrix consists of red/brown micritic pedogenic carbonate indicating the introduction of terrestrial soils during extreme weather events. Calcrete rinds are common around smaller extraclasts and mollusc fragments, and vugs contain blocky calcite cements.

Pleistocene units

Late-Pleistocene (Last Interglacial MIS 5e) reef unit (Fig. 4.5F–J).

The Last Interglacial (MIS 5e) Tantabiddi reef unit underlies the Holocene unit forming buildups from ~1.5–4.5 m. The top 10–20 cm is blackened and highly calcretised (Fig. 4.5F) forming a well cemented pedogenic caliche crust, a result of relatively long periods of subaerial exposure in this arid environment. Below the calcrete the unit is preferentially stained grey from leaching for 1–1.5 m (see Fig. 4.4). Where leaching is minimal the unit is well cemented with corals containing red/brown stain and infill from terrigenous alluvium.

Domal coral framestone facies dominates forming buildups up to ~4.5 m. Two zones of domal growth are present, a deeper offshore unit and a shallow unit separated by detrital facies. Minor red coralline algal bindstone consists of thick laminated algal crusts (*Mesophyllum* and *Lithophyllum*) on minor tabulate corals (Fig. 4.5G, H). This shallow-water facies only occurs in one core (MBH13) ~20 cm thickness. Arborescent coral framestone facies form buildups up to ~2 m. Carbonate sand facies (rudstone and grainstone) is common filling interstices in the coral framework and a bioclastic rubble facies (packstone, rudstone, floatstone) forms buildups up to 3 m in leeward cores. It consists of mixed coral, molluscan and algal gravel with rounded to subrounded granules and pebbles of Tertiary and Pleistocene limestone (b5 cm) supported in a red/brown, bioclastic matrix (Fig. 4.5F, I, J). This facies is interpreted as a shallow-water foreshore assemblage that has components from the adjacent reef and pavements, with injections of alluvial fan and eroded Pleistocene platform deposits. It is similar to the Tantabiddi foreshore facies identified on the west side of Cape Range (Wyrwoll et al., 1993). This facies is interrupted by intervals (~20 cm thick) of domal *Porites* corals.

Mid-Pleistocene (MIS 7?) bioclastic conglomerate facies (Fig. 4.5K).

This unit is similar to the Last Interglacial bioclastic rubble facies but is separated by a strong calcrete and contains a high proportion of terrestrial pebbles and quartz grains. It forms buildups up to 4 m in leeward cores and correlates with the Mowbowra Conglomerate Member of the Bundera Calcarenite, representing a series of foreshore- beach sequences with stream-gravel injections during high discharge events (Wyrwoll et al., 1993). Its type section is located south of the core site at Mowbowra Creek (Figs. 4.2D and 4.3F, G). The age of this unit has not been confirmed but on the basis of stratigraphic succession it may correspond to MIS 7.

Pleistocene alluvial fanglomerate facies (Fig. 4.5L).

Sediments of alluvial fanglomerates are dominated by pebble-sized conglomeratic clasts of Tertiary limestones. There is a strong calcrete zone at the boundary with the bioclastic conglomerate facies above. This facies is well lithified and has no obvious marine influence.

4.4.3. Timing and nature of reef accretion

The results of U-series dating are given in Table 4.1. The Thompson open-system age for the pre-Holocene foundation (sample MBH13/01) did not yield reliable U-series dates due to multiple post depositional processes, including diagenesis and U loss. The date (154 ka BP) does however confirm the foundation to be mid- to late- Pleistocene in age. Two dates from stratigraphically equivalent corals at Maxwell Point returned open-system ages which fall within the range of MIS 5e (129.5 and 131.1 ka BP).

Holocene framework corals arewell preservedwith reliable U-series dates of 7.93–5.8 ka BP (Table 4.1). The oldest date was from the base of the most seaward core (MBH1) and represents the age of the preserved material and not necessarily timing of reef initiation. The reef however grew *in-situ* due to the lack of reworked material. Reef accretion curves for core dates are shown in Fig. 4.6A alongside a curve of best fit to illustrate the trend in decreasing growth rates. The curve indicates an initial rapid phase with a trend of slowing accretion centered ~7 ka BP. Calculated vertical accretion rates are shown in Table 4.1 and Fig. 4.6B and expressed as mm/year. Vertical accretion rates range from 9.88–1.46 mm/year with an average of 4.11 mm/year. The highest rate of accretion occurred in the most seaward and deepest Holocene core (MBH1) composed of massive coral framestone and coralline algal crusts. Two cores (MBH1 and 6) contained corals dated at their base, middle and top allowing a comparison of accretion rates during the Holocene (Fig. 4.6B).

Both cores demonstrate higher accretion rates in the lower half of the cores (1a=9.88 and 6a=5.49 mm/year) with a decrease in rates up-core (1b=3.55 and 6b=1.46 mm/year). There is a

Table 4.1

U-series TIMS ages for corals in reef cores from the eastern Ningaloo Reef, Exmouth marina site, WA.

Sample name	Depth/ altitude (m)	Coral ID	U (ppm)	^{232}Th (ppb)	(^{230}Th/ ^{232}Th)	(^{230}Th/^{238}U)	(^{234}U/ ^{238}U)	Uncorr. ^{230}Th age (ka BP)	Corr. ^{230}Th age (ka BP)	Corr. initial (^{234}U/ ^{238}U)	δ^{234}U(T)	Open-system age (ka BP)	Accretion (mm/yr)
MBH1/01	-4.36	*Pocillopora*	3.9491 ± 35	1.565	524.4	0.06850 ± 21	1.1465 ± 11	6.691± 23	**6.681± 23**	1.1493 ± 12	149.3 ± 12		
MBH1/03	-6.39	*Platygyra*	2.6475 ± 28	0.131	4554.7	0.07422 ± 25	1.1488 ± 16	7.254 ± 28	**7.253 ± 28**	1.1518 ± 16	151.8 ± 16		**9.88**
MBH1/06	-8.83	*Montipora*	4.3769 ± 62	25.815	40.1	0.07791 ± 41	1.1452 ± 15	7.652 ± 43	**7.500 ± 86**	1.1486 ± 16	148.6 ± 16		**3.55**
MBH2/01	-3.66	*Goniopora*	3.3550 ± 35	11.484	59.5	0.06711 ± 43	1.1528 ± 17	6.515 ± 44	**6.427 ± 62**	1.1557 ± 17	155.7 ± 17		
MBH2/03	-7.01	*Porites*	3.5587 ±23	20.975	40.3	0.07831 ± 27	1.1514 ± 09	7.649 ± 28	**7.498 ± 80**	1.1549 ± 09	154.9 ± 09		**3.13**
MBH3/01	-3.99	*Lobophyllia*	2.3512 ± 29	26.676	18.2	0.06794 ± 68	1.1476 ± 17	6.628 ± 69	**6.336 ± 161**	1.1507 ± 18	150.7 ± 18		
MBH3/03	-7.34	*Favities*	2.5849 ± 30	0.473	1188.6	0.07169 ± 27	1.1482 ± 21	7.002 ± 30	**6.998 ± 30**	1.1512 ± 21	151.2 ± 21		**5.07**
MBH4/02	-6.11	*Montipora?*	3.6752 ± 44	7.098	115.3	0.07342 ± 36	1.1458 ± 19	7.192 ± 39	**7.143 ± 46**	1.1489 ± 20	148.9 ± 20		
MBH4/03	-7.81	*Symphyllia*	3.4000 ± 29	83.507	10.7	0.08694 ± 50	1.1465 ± 12	8.563 ± 52	**7.929 ± 318**	1.1508 ± 13	150.8 ± 13		**2.16**
MBH5/01	-5.55	*Porites*	3.6547 ± 57	1.059	750.5	0.07170 ± 21	1.1475 ± 17	7.007 ± 23	**7.000 ± 24**	1.1505 ± 17	150.5 ± 17		
MBH5/02	-7.70	*Porites*	4.7096 ± 63	4.109	268.6	0.07722 ± 31	1.1447 ± 17	7.585 ± 33	**7.562 ± 35**	1.1479 ± 18	147.9 ± 18		**3.83**
MBH6/01	-4.06	*Plesiastrea ?*	3.1607 ± 208	2.822	207.6	0.06108 ± 65	1.1703 ± 78	5.823 ± 75	**5.800 ± 76**	1.1731 ± 79	173.1 ± 79		
MBH6/02	-5.49	*Cyphastrea ?*	3.8740 ± 51	6.267	130.8	0.06973 ± 37	1.1456 ± 18	6.820 ± 39	**6.779 ± 44**	1.1485 ± 18	148.5 ± 18		**5.49**
MBH6/05	-7.61	*Porites*	3.5414 ± 42	10.568	75.1	0.07387 ± 33	1.1453 ± 13	7.242 ± 34	**7.165 ± 51**	1.1484 ± 13	148.4 ± 13		**1.46**
MBH11/01	-3.23	*Astreopora?*	3.5770 ± 40	0.253	2873.9	0.06692 ± 22	1.1484 ± 18	6.521 ± 24	**6.519 ± 24**	1.1512 ± 19	151.2 ± 19		
MBH11/02	-4.53	*Cyphastrea*	3.3208 ± 94	0.281	2588.3	0.07213 ± 38	1.1481 ± 27	7.047 ± 42	**7.045 ± 42**	1.1511 ± 27	151.1 ± 27		**2.47**
MBH13/02	-3.28	*Porites*	2.9920 ± 43	1.328	6257.2	0.91499 ± 258	1.1191 ± 17	174.8 ± 1.4	174.8 ± 1.4	1.1954 ± 25	195.4 ± 25	**154 ± 2.0**	
L16905.1	1.5	*Favities*	3.2849 ± 47	0.242	36512.1	0.88701 ± 20	1.1361 ± 26	156.5 ± 1.2	156.5 ± 1.2	1.2121 ± 36	212.1 ± 36	**129.5 ± 2.3**	
L16905.4	1.5	*?*	2.8692 ± 40	0.366	21434.4	0.90098 ± 23	1.1387 ± 22	161 ± 1.2	161 ± 1.2	1.2189 ± 30	218.9 ± 30	**131.1 ± 2.0**	

Note: U-series TIMS analytical procedures were those described in Zhao et al. (2001) and Yu et al. (2006). U-series open-system ages were calculated using the model of Thompson et al. (2003). All errors are quoted at 2 sigma level for the least significant digits.

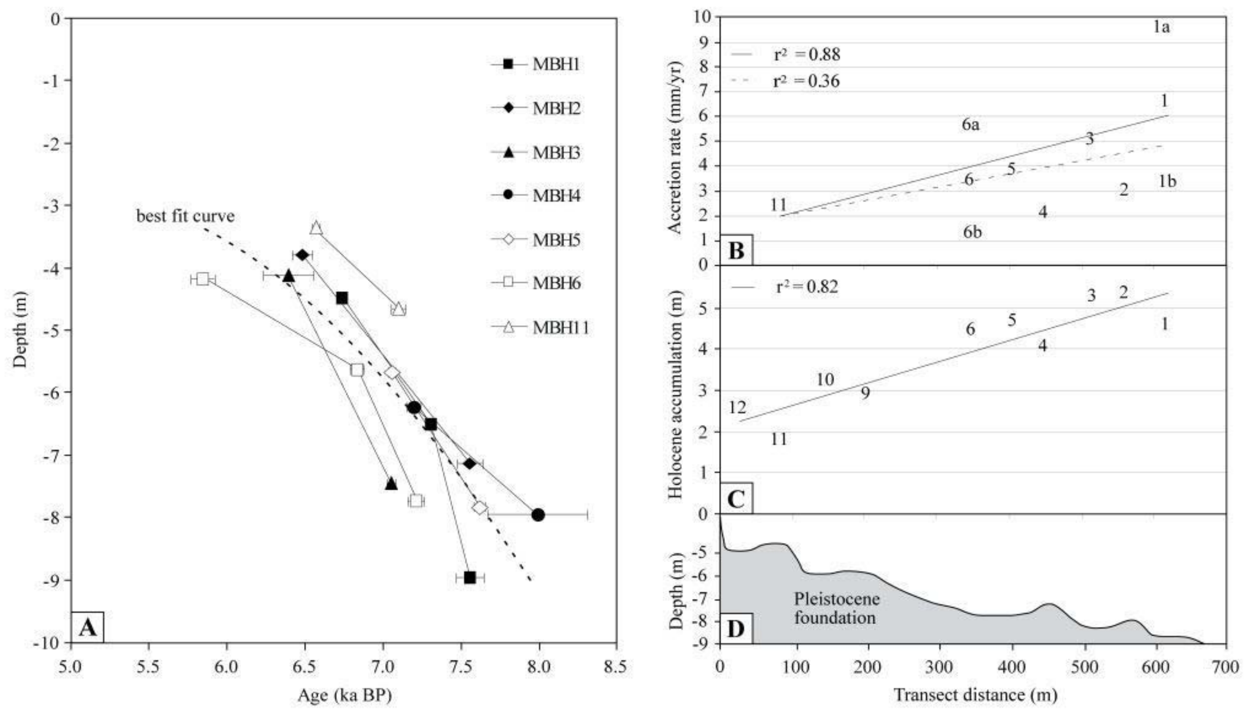

Figure. **4.6**. (A) Holocene vertical reef accretion curve and polynomial curve of best fit (n=2) for Exmouth marina core data, WA. (B) Holocene reef accretion rate against distance along core transect, with line and measure of best fit. Numbers refer to core labels. Average of accretion rates for 1a, b (1) and 6a, b (6) has been used in trend analysis, solid line excludes outliers (cores 4 and 2) and dotted line is trend for all core data. (C) Holocene accumulation against distance along core transect, with line and measure of best fit. (D) Morphology of Pleistocene foundation.

significant trend of decreasing vertical accretion rates landward across the core transects (r2=0.88) (Fig. 4.6B). The exceptions are cores MBH2 and 4 which initiated growth on Last Interglacial topographic highs, limiting the available accommodation needed for optimal coral growth (r2=0.36 with outliers 2 and 4 included). Holocene accumulation ranges from 1.8–5.3 m with thickest accumulation occurring in the deepest seaward cores. There is also a significant trend in decreasing accumulation thickness across the core transect (r2=0.82) (Fig. 4.6C).

Antecedent topography and slope (Fig. 4.6D), and their effect on accommodation, accretion rates and accumulation are important factors in these trends but this does not take into consideration timing of reef accretion, sea-level influence and differences in facies accretion rates. Reef accretion rates are highest in seaward cores dominated by domal coral facies. The trend of decreasing vertical accretion rates landward also correlates with an increase in the dominance of arborescent coral framework and associated rubble, mixed domal/ arborescent facies and detrital infill inshore.

4.4.4. Holocene fringing reef structure and facies

A cross-section of the core transect with major facies and isochrons (lines linking equivalent ages) is illustrated in Fig. 4.7. The Holocene fringing reef developed over shallow sloping Last Interglacial reef substrates. The internal structure of the Holocene is dominated by two major zones of in-situ coral framework, a deeper outer and a shallow inner reef zone which are separated and capped by detrital infill. The antecedent topography is one of the main controlling factors of Holocene reef accretion. The Last Interglacial surface consists of distinct topographic highs which can be grouped into the inner, middle and outer platforms. The middle and outer platforms consist of double peaks in morphology ~100 m apart. The Holocene reef grew and mimicked this morphology, becoming less prominent during the latter stages of development. The outer platform at the seaward edge of the cored transect (~8.5–8m depth) is the site of the earliest Holocene growth (7.93 ka BP). This double outer Holocene reef grew vertically and landward with the seaward reef becoming increasingly dominant, attributed to higher vertical accretion rates on the seaward margin.

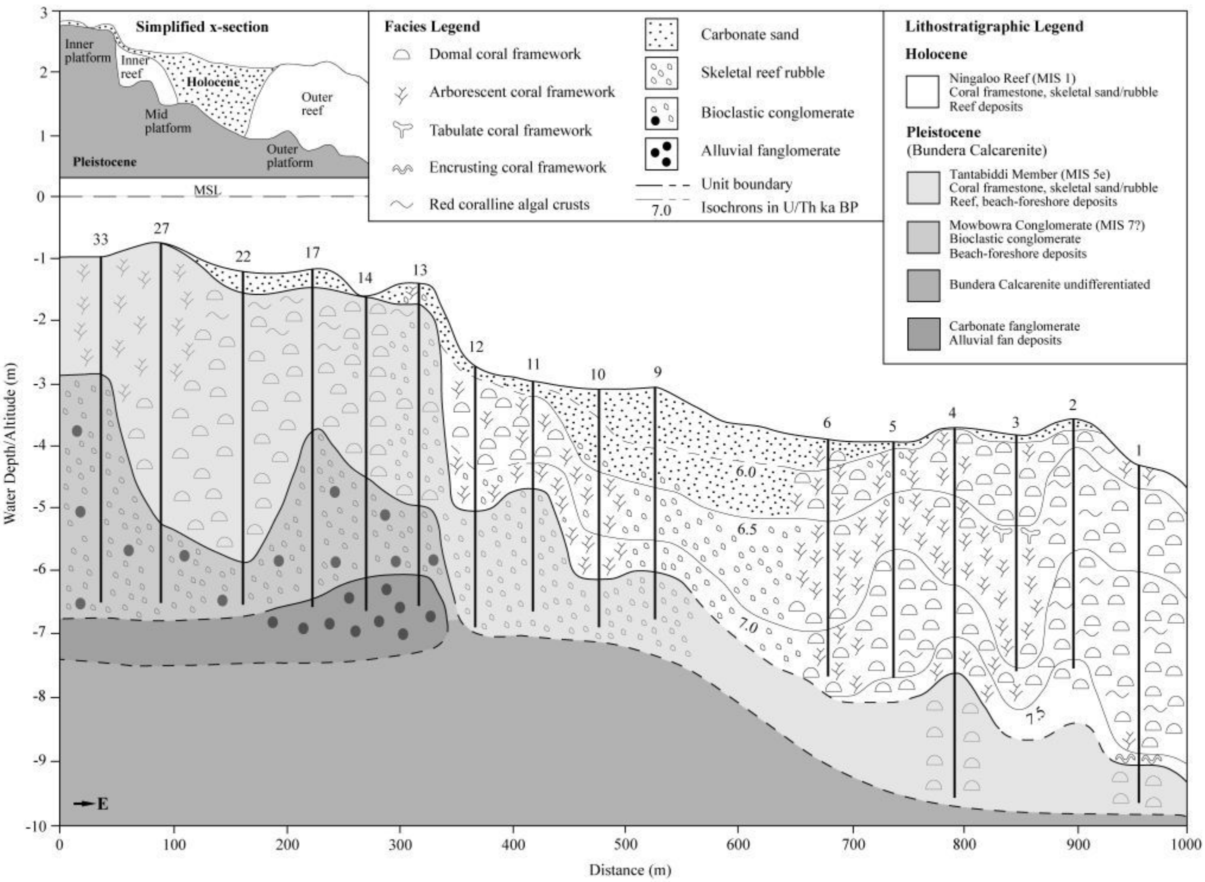

Figure.**4.7**. Full cross-section with isochrons and summary of facies for Exmouth marina transect, WA. Simplified cross-section includes terminology used in text. Dashed lines are inferred boundaries/dates.

Shoreline back-stepping onto the middle platform (in ~6–4.5 m depth) occurred at ~7.3 ka BP creating two major Holocene reef zones within the system. The inner reef zone accreted vertically until its demise ~6.5 ka BP. The region between the inner and outer reef zones was infilled with skeletal reef rubble during earlier stages of development, with an increase in the influence of both reef and terrigenous sediments at ~6.5 ka BP. Detrital buildup continued during and after the reef's demise and currently forms a veneer over the Holocene reef framework. The inner Last Interglacial platform (in ~2–1 m) forms the modern subtidal–intertidal algal-dominated pavement. No framework growth occurred on this platform during the Holocene, only the formation of a detrital veneer.

The reef structure is comparable to the early stages of the Pleistocene reefal substrate model defined by Hopley and Partain (1987) and modified by Smithers et al. (2006), for fringing reefs of the Great Barrier Reef. In this case detrital infill and progradation dominate latter stages of development with no framework progradation due to the early demise of the reef system. The overall reef development resembles the generalised aggrading and back-stepping models defined by Kennedy and Woodroffe (2002) and modified by Montaggioni (2005). Holocene reef development is heterogeneous in nature with significant variation in facies over relatively short distances. There are however distinct patterns both vertically and laterally reflecting changing environmental conditions (Fig. 4.7).

4.5. Discussion

4.5.1. Pleistocene foundations

Suitable substrates are vital for reef colonisation and subsequent reef growth (Veron, 1995) and the type of substrate is thought to affect the reef's ‘start-up’ period (Cabioch et al., 1995; Smithers et al., 2006). Last Interglacial reefs are the most common antecedent surface on which Holocene reefs have established (Hopley et al., 1978) and in the GBR they are generally the earliest to be colonised (Smithers et al., 2006).

The relationship between Holocene and Last Interglacial (MIS 5e) phases of development of the Ningaloo Reef is clearly shown in core data for this study and in the earlier work of Collins et al. (2003). On the more extensive western Ningaloo Reef, the Holocene colonised the seaward margin of the Last Interglacial reef forming a buildup of ~10–15 m below the reef crest. On the eastern Ningaloo Reef, the Holocene initiated on Last Interglacial platform highs and mimicked the topography throughout its development, further influencing available accommodation, reef accretion rates, morphology and facies development. The slope of the Last Interglacial substrate provided the accommodation for rapid growth on the seaward margin by massive corals with coralline crusts, which subsequently provided the protection for lower energy arborescent and mixed communities to thrive inshore.

The Last Interglacial reef was widespread in WA and reef communities were more extensive than today occurring in a single biogeographic province during a warmer period and more intense Leeuwin current (Collins et al., 2003; Greenstein and Pandolfi, 2008). Holocene coral reefs have since shifted their ranges northwards in a zone where both temperate and tropical provinces overlap (Greenstein and Pandolfi, 2008). Interbedding of Last Interglacial reef units with the Mowbowra Conglomerate in outcrop atMowbowra Creek, indicates active stormand cyclone activity during this time. Cyclone activity also occurred earlier in the Pleistocene as seen by underlying alluvial fanglomerate deposits.

4.5.2. Holocene sea-level and reef growth

Holocene reefs can be attributed to a reef growth phase (RGIII) which occurred after major postglacial meltwater pulse events and associated non-constructional or reef drowning periods (Montaggioni, 2005). A number of studies have inferred 'stepped' sea-level rise during the Holocene, attributed to meltwater pulse events including MWP-1C (~9.8–9.0 ka BP) (Liu et al., 2004), an 8.4–8.2 ka BP event (Blanchon and Shaw, 1995; Barber et al., 1999; Teller et al., 2002; Yim et al., 2006; Liu et al., 2007) and the cold '8.2 ka event' (Alley et al., 1997; Clark et al., 2001). Recent sea-level data from the farfield location of Singapore (Bird et al., 2007) indicates a slowdown or cessation (stillstand) of sea-level centered at ~7.7 cal BP for a period of several hundred years. Blanchon and Shaw (1995) reported an additional 'catastrophic' MWP-2 (~7.6–7.5 ka BP) for the Caribbean following a period of erosion, with renewed coral growth backstepping upslope and inshore at ~7.1 ka BP. Bird et al. (2007) also recognised a resumption of sea-level between 7.4 and 7.2 ka BP of similar magnitude to MWP-2. Many reefs are thought to have recovered due to the availability of accommodation from the preceding meltwater event, leaving no resolvable framework record (Blanchon et al., 2002; Camoin et al., 2004; Bird et al., 2007).

In WA the continent is relatively tectonically stable and as a consequence less affected by glacio-isostatic adjustment due to its 'farfield' location (Collins et al., 2006b). A composite Holocene sea-level curve has been recorded from the Houtman Abrolhos Islands using U-series dating of emergent, cemented coral shingle pavement (Collins et al., 2006b) and reef core data from Morley Island which resembles a 'keep-up' reef mode (Collins et al., 1993; Eisenhauer et al., 1993). The Morley core is situated on the semi-exposed to sheltered, leeward side of the island and deemed appropriate to compare with the core in this study.

To place the development of the eastern Ningaloo Reef into context, a comparison has been made with a modified Houtman Abrolhos sea-level curve (Fig. 4.8). The Holocene transgression in WA shows a number of inflections suggesting a stepped sea-level rise which may correlate to Holocene meltwater pulse events. From ~10– 9.6 ka BP sea-level rose moderately at rates of ~6.25 mm/year in depths of ~22–20 m. From ~9.6–9.4 ka BP there was an increase in sea-level

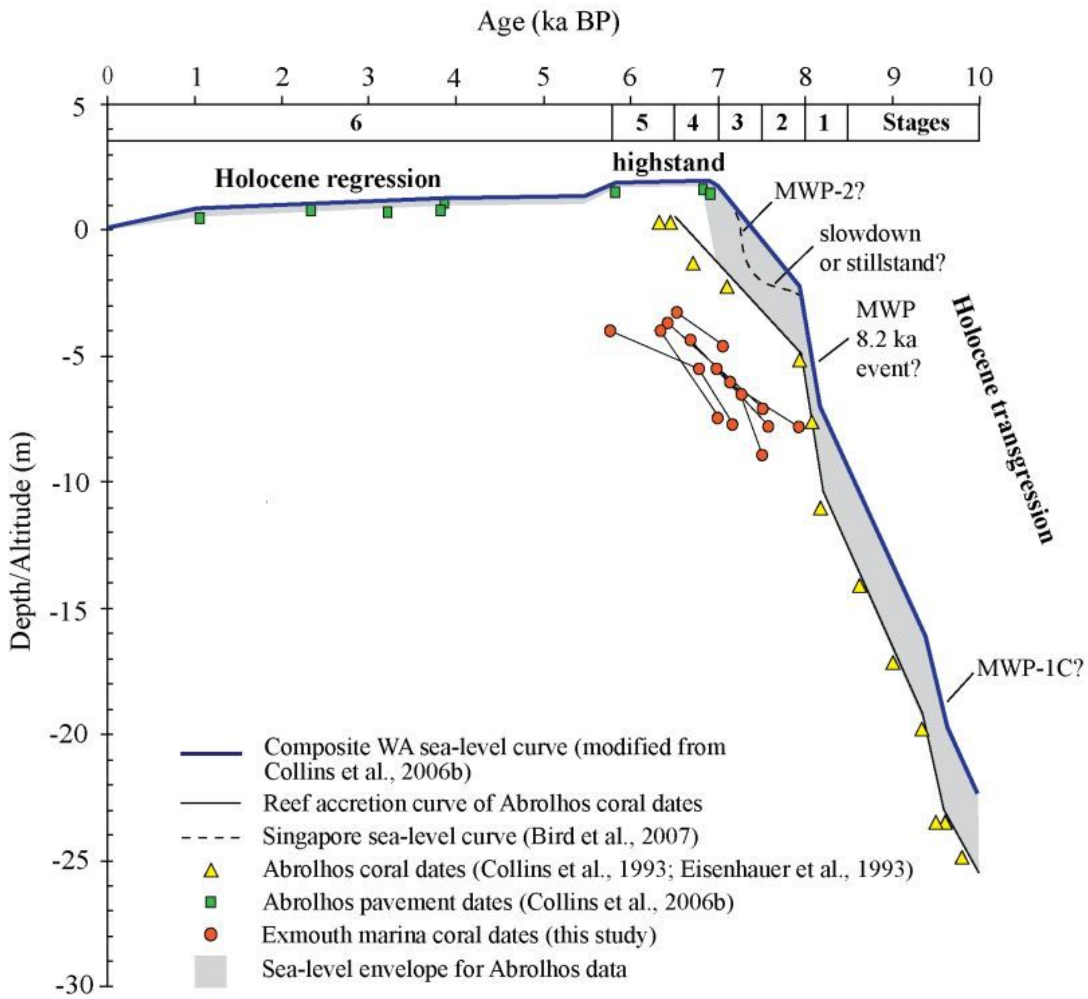

Figure 4.8. Composite Holocene sea-level curve for the Houtman Abrolhos Islands, WA, modified from the curve in Collins et al. (2006b) and constructed from U-series dating of emergent, cemented coral shingle pavement (Collins et al., 2006b) and U-series dating of corals in core from Morley Island ('keep-up' reef mode) (Collins et al., 1993; Eisenhauer et al., 1993). The curve is based on MSL and all dated sample depths have been corrected. Sample ages are given in ka BP. An envelope of 0.4 m above Abrolhos pavement dates (squares) represents the estimate of actual sea-level. A line of best fit for the Abrolhos coral data (triangles) represents maximum vertical accretion and minimum limit for sea-level. Abrolhos pavement dates plot ~3 m above corresponding coral dates on the reef accretion curve for the Abrolhos. An envelope of 3 m above the Abrolhos coral data has therefore been plotted to represent an estimate of actual sea-level. This is consistent with a 'keep-up' mode of accretion. This envelope assumes that the coral record tracked sea-level and does not take into consideration factors such as time lag for initiation, erosion and true depths of corals. U-series dating of Exmouth marina corals (circles) from this study are also illustrated (see detailed accretion curve in Fig. 4.6). The composite sea-level curve is comparable to that constructed for the Indo-Pacific region (Montaggioni, 2005). Additional data from Bird et al. (2007) is included to illustrate a slowdown/stillstand and meltwater event not represented in the WA data. Refer to Fig. 4.9 and text for information on development stages 1–6.

from depths of ~20–16 m with rates of ~18 mm/year. During this time postglacial sea-level would have breached the 19 m deep Exmouth sill and inundate the Exmouth Gulf embayment. From ~9.4–8.2 ka BP sea-level rates dropped to ~7.5 mm/year until a marked increase at ~8.2–8 ka to rates of ~22 mm/year, where sea-level may have 'jumped' from depths of ~7–2.5 m. The slowdown/ stillstand of Bird et al. (2007) and subsequent meltwater pulse identified by Blanchon and Shaw (1995, MWP-2) and Bird et al. (2007) may not be represented in the Abrolhos coral framework record due to the lack of data during this period and availability of accommodation for continued accretion.

4.5.3. Chronology of Holocene reef development

A chronology of Holocene reef accretion and facies development in relation to fluctuating sea-level is illustrated in Fig. 4.9. Paleo-depths have been determined by comparing the position of reef core dates to the sea-level curve in Fig. 4.8. An estimation of average reef accretion rates within each stage has been determined using reef accumulation and isochron data in Fig. 4.7. The following six stage chronology is proposed for the eastern Ningaloo Reef.

Coastal inundation (8.5–8.0 ka BP)

Last Interglacial platforms in depths of 9 m were inundated at ~8.5 ka BP and by ~8 ka BP sea-level had risen over 6 m to depths of ~2.5 m. This rapid increase in sea-level may be attributed to a meltwater event represented in the WA sea-level curve at ~8.2 ka BP. Despite the available accommodation and substrate no colonisation occurred. This may have been a result of high rates of sea-level change detrimental to coral growth and the potential for increased terrestrial sediment input and turbidity during initial flooding (Hopley, 1994).

Reef initiation 'start-up' (8.0–7.5 ka BP)

There was an increase from depths of ~2.5 m to depths similar to modern sea-level by 7 ka BP. The outer Last Interglacial platform high provided the ideal site for reef development and the outer Holocene reef initiated at ~7.9 ka BP in paleo-depths of between 5 and 7 m. Coral growth during this 'start-up' period included predominantly mixed and domal coral communities, with the only colonisation of encrusting facies for the entire transect occurring at the base of the windward slope in paleo-depths of ~6.5–7 m. The reef accreted ~1 m above the antecedent substrate with a mean accretion rate of ~2 mm/year. Bird et al. (2007) suggest a slowdown or stillstand in sea-level at this time (Figs. 4.8 and 4.9). Although this is not represented in the WA curve, it may explain the limited accretion during this time.

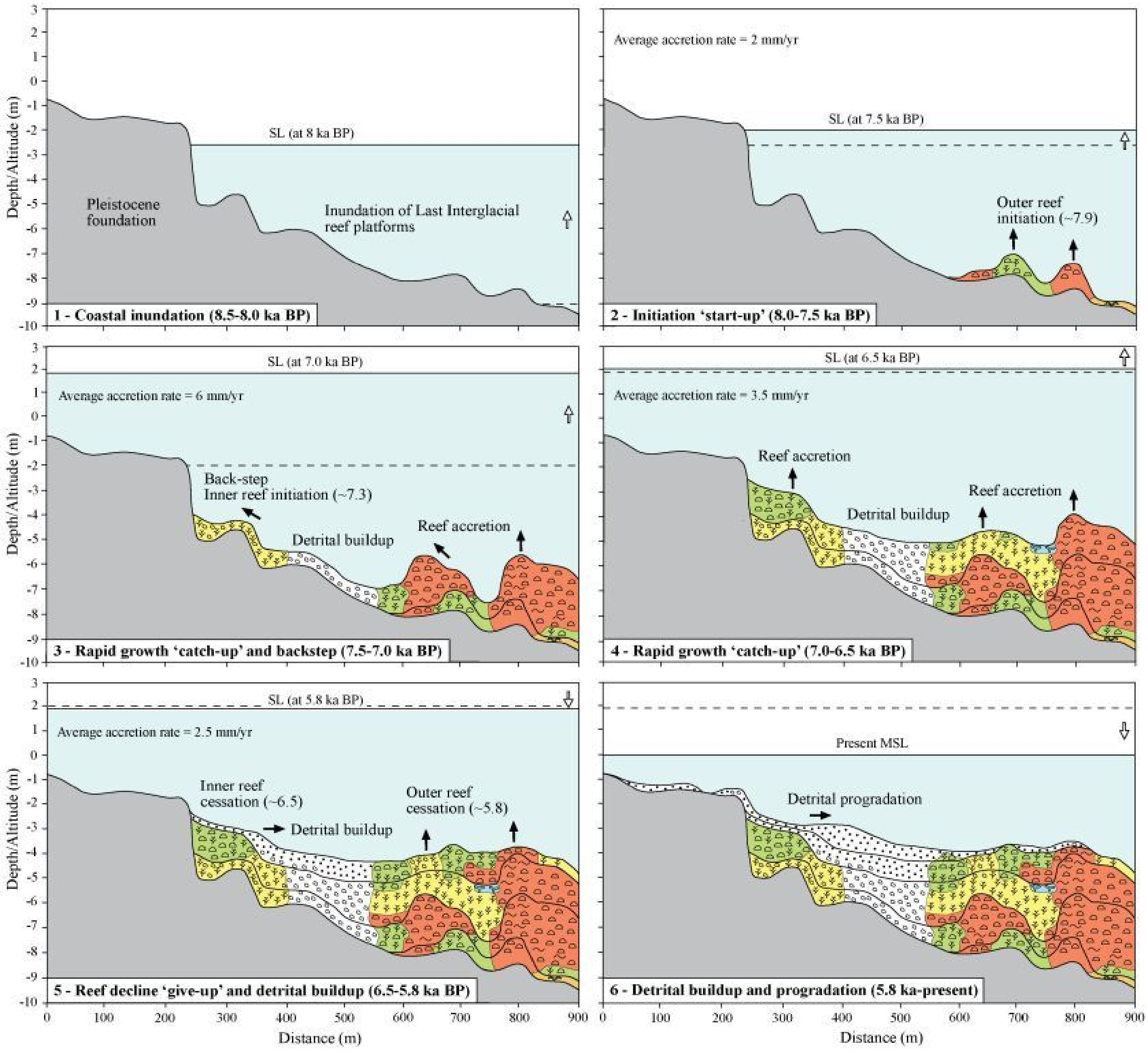

Figure. 4.9. Chronology of reef and facies development from 8.5 ka BP to the present, Exmouth Gulf, WA. Refer to Fig. 4.7 for reef facies legend and details of isochrons (solid lines); colours or grey shades correspond to particular facies and illustrate changes during the Holocene. Solid arrows refer to the nature and direction of accretion. Sea-level data is based on the composite sea-level curve of WA (refer to Fig. 4.8). Open arrows refer to a fall or rise in sea-level for the stage. Additional data has been included in stages 2 and 3 from the sea-level curve in Bird et al. (2007) to illustrate events that may be relevant to reef development in this study.

Rapid growth 'catch-up' and back-step (7.5–7.0 ka BP)

Sea-level rose to+1.8 m approaching the Holocene highstand, but a metre scale 'jump' during MWP-2 (Blanchon et al., 2002; Bird et al., 2007) is not recorded. The stratigraphy and accretion rates in this study indicate that an event of similar magnitude may have occurred. There was a rapid period of accretion as corals on the outer reef grew rapidly to 'catch-up' to sea-level. Accretion rates reached as high as 9.11 mm/year and the reef accreted vertically up to 3 m with a mean accretion rate of ~6 mm/year. Domal corals with algal crusts dominated the outer reef in paleo-depths of ~7–8 m. The timing of back-stepping at ~7.3 ka BP, to shallower Last Interglacial substrates, is consistent with this reported rapid increase in sea-level. The inner reef formed during this back-stepping event and was dominated by arborescent corals in paleo-depths of ~3–

7 m. Holocene growth continued to accentuate the relief of the underlying Last Interglacial topography. Detritus of skeletal rubble began to accumulate between the inner and outer reefs from the erosion of reef framework and increased coastal erosion and flooding during sea-level rise.

Rapid aggradational growth 'catch-up' (7.0–6.5 ka BP)

A marked slowdown in sea-level at ~7.0 ka BP to ~1.5 mm/year continued for ~200 years before the onset of the Holocene highstand, which reached a height of ~+2 m at ~6.8 ka BP (Collins et al., 2006b). The availability of accommodation allowed for continued growth of corals in 'catch-up' mode. The reef system accreted vertically with buildups of ~1.5–2 m and a decrease to a mean accretion rate of ~3.5 mm/year. Massive corals with algal crusts continued to dominate the windward margin in paleo-depths of ~6–7 m with slower accretion rates than previous. Arborescent corals began to colonise the landward side of the outer reef in paleo-depths of ~7–9 m, a result of the enhanaced protection from the continuing aggradation of seaward margin. Arborescent growth continued on the deepest parts of the inner reef zone in paleo-depths of ~6–8 m, with mixed communities colonising the shallowest reef in ~4.5–6 m. Holocene growth continued to accentuate the relief of the underlying topography and detrital buildup of coarse skeletal rubble continued to infill the space between the inner and outer reefs.

Reef decline 'give-up' and detrital buildup (6.5–5.8 ka BP)

Sea-level stabilised after the Holocene highstand and began to fall towards the end of the stage. Although there was available accommodation conditions became unfavourable for continued growth on the inner reef at ~6.5 ka BP and a veneer of carbonate sand began to dominate the inshore region, sourced from a mixture of modern skeletal material, erosion of Last Interglacial platforms and terrestrial alluvial deposits from storm/cyclone activity. The outer reef became isolated offshore and growth continued vertically forming buildups of 1–1.5 m with a marked decrease in mean accretion to ~2.5 mm/year. Communities of arborescent and mixed corals began to dominate the outer reef in paleo-depths of 6–7 m before reef growth cessation at ~5.8 ka BP.

Detrital buildup and progradation (5.8–present)

Holocene sea-level regressed to current levels and the dominant process during this time was detrital buildup and progradation of carbonate sands with a high proportion of terrestrial detritus, completely submerging the inner reef and forming a veneer over the outer reef. The modern reef is dominated by a subtidal Last Interglacial limestone pavement inshore which is highly bored, well cemented and algal-dominated. The Holocene outer reef surface has a sand veneer in places and where exposed is partially cemented forming local, algal-covered hardground deposits. The antecedent topography is no longer a contemporary geomorphic feature which may have been accentuated by erosion during the regression.

4.5.4. Holocene reef growth and demise during environmental change

Understanding the mechanisms that may have contributed to the cessation of reef growth in this study is important for predicting modern reef response to climate change and other anthropogenic impacts globally. The reason for the demise of reefs during the Holocene is complex and may involve a combination of factors (Beaman et al., 2008; Harris et al., 2008), including burial by sediments, declining water quality, excess nutrients, changes in water turbidity, sea surface temperature or irradiance, reduction in larval dispersion due to changes in water circulation, severe storms, and drowning as a result of rapid increases in sea-level during the Holocene transgression (Hallock and Schlager, 1986; Macintyre, 1988; Blanchon and Shaw, 1995; Montaggioni, 2000; Kleypas et al., 2001; Masse and Montaggioni, 2001; Blanchon et al., 2002; Montaggioni, 2005; Macintyre et al., 2007; Smithers et al., 2007; Beaman et al., 2008; Harris et al., 2008).

Holocene reef accretion rates indicate that reefs should be able to keep pace with sea-level change, yet drowned ‘give-up’ reefs are common in the geologic record (Hallock and Schlager, 1986). Fringing reefs are generally thought to be less likely to be drowned because of the availability of substrates for the reef to back-step to shallower depths in the face of rapidly rising sea-level (Kennedy and Woodroffe, 2002; O'Leary et al., 2008). Back-stepping of the eastern Ningaloo Reef occurred alongside a dramatic increase in reef accretion rates between 7.5–7 ka BP, which provided the accommodation at optimal depths for carbonate production and continued rapid growth.

Reef back-stepping can be caused by compromised calcification of corals in the face of rapidly rising sea-level (Hubbard et al., 1997) and this may have occurred during an event of similar magnitude to MWP-2 (Blanchon et al., 2002). Favourable conditions persisted until the Holocene highstand (~6.8 ka, Collins et al., 2006b) but growth slowed during sea-level stabilisation and finally ceased during the subsequent regression. Despite the availability of accommodation and suitable substrates, conditions became unfavourable for growth on the inner reef at ~6.5 ka BP and the outer reef at ~5.8 ka BP. Reef growth was therefore accommodation-independent and other driving factors alongside sea-level change were responsible for the reef's demise.

A more likely source of stress, as a consequence of rising sea-level, was flooding and erosion of the coastal plain and shoreline during the mid-Holocene highstand. As Holocene sea-level stabilised during the highstand, bioclastic sands with a high proportion of terrestrial detritus (eroded Pleistocene platform deposits, thin sheets of distal alluvial sediment, colluvial soils and aeolian-derived sediment) began to accumulate and prograde seaward over the reef framework. This is likely to have led to an increase in coastal turbidity and a decline in water quality as identified in regions subject to increased sedimentation (Macintyre, 1988; Kleypas, 1996; Smithers and Larcombe, 2003). Sediments which settle on coral colonies and cause high turbidity can disturb the reef production/sediment balance leading to changes in coral assemblages and/or the demise or 'turn-off' of established reefs (Buddemeier and Hopley, 1988; Rogers, 1990; Cortes et al., 1994; Woolfe and Larcombe, 1999). This change to more stressful conditions may have been responsible for a marked shift in communities prior to reef demise, from inner reef arborescent to mixed coral facies, and outer reef domal to mixed coral facies, alongside a slow-down in accretion at this time. Mixed communities were also common during the slow reef 'start-up' period suggesting they may have been more tolerant to these conditions.

An alluvial mud interval on top of the inner reef prior to its demise and the high proportion of alluvial material filling interstices in the framework, suggests that severe storm/cyclone events resulted in episodic terrigenous sediment accumulation and periods of high and prolonged turbidity as occurs today. This would have contributed to the demise of an already stressed community. McIlwain (2002) identified increased turbidity within the Gulf after cyclone activity, with high levels of suspended sediment in the water column reducing visibility to b2 m lasting for a period of ~4 months. During Cyclone Vance in 1999 coral mortality was widespread due to smothering by increased turbidity and mud. Increased sedimentation and freshwater run-off during these events may be infrequent but can be cataclysmic to fringing coral reefs (Kennedy and Woodroffe, 2002). In addition to increasing runoff, sedimentation and turbidity, cyclones also impact the reef by physically destroying the coral framework with coral rubble/shingle banks at Bundegi reef formed during cyclone activity. It is likely that these significant erosional and depositional events are the dominant mechanism, in this otherwise low energy setting, for detrital buildup of coral debris within the core transect.

4.5.5. Analogue for modern coral reefs under environmental change

Environmental change to coral reefs can be both natural and anthropogenic in origin, but human activities frequently amplify these naturally occurring stresses (Hallock et al., 2004). Climate change impacts of the greatest concern to coral reef ecology and geomorphology include increases to sea surface temperatures, sea-level, ocean acidity and storm severity. The degradation of reefs is also likely to be severe when combined with other anthropogenic impacts such as declining water quality (Hoegh-Guldberg, 2006; Smithers et al., 2007). This study demonstrates that a combination of natural processes (fluctuating sea-level, flooding, increased sedimentation and turbidity, alongside severe storm activity) likely contributed to changes in reef accretion and biofacies, and the ultimate demise of a section of the eastern Ningaloo Reef during the mid-Holocene. A shift to non-reef-building occurred naturally and is indicative of a degraded coral community during environmental disturbance (Van Woesik et al., 1999). Changes to the frequency and scale of disturbances are pushing many coral reef ecosystems from coral to algal-dominated states (McCook et al., 2007) and maintaining the resilience of coral reefs after disturbances (e.g. cyclone impacts or flooding) is central for the preservation of these ecosystems in ecological timescales (Hoegh-Guldberg, 2006).

The geomorphology and ecology of reefs are strongly interdependent and where climate change and other anthropogenic impacts affect geomorphological features it will often be accompanied by ecological change and vice versa (Smithers et al., 2007; Perry et al., 2008). The impact of disturbance from changes in the balance of reef construction and erosion, and therefore long-term geomorphological processes, may critically influence coral reef communities (Smithers et al., 2007; Perry et al., 2008). Geomorphology is uniquely positioned to offer an integrative perspective of reef condition that is at a scale appropriate for many climate change assessments (Smithers et al., 2007). This sequence of data, integrating reef development processes with the response to environmental change, can be used as an important starting point in the assessment of future pressures on coral reefs globally.

4.6. Conclusions

Analysis of the internal structure of the eastern Ningaloo Reef has provided a clear insight into Holocene reef growth during environmental change. The Last Interglacial reef provided the substrate for Holocene reef initiation and further influenced reef accretion rates, facies development and reef morphology. The Holocene reef deposited through aggradation and back-stepping during the Holocene transgression with minor accretion during the subsequent highstand, finally ceasing growth during the onset of the late-Holocene regression. The reef was not able to ‘keep-up’ with sea-level despite the available accommodation and as a consequence formed an incipient reef morphology throughout its evolution.

Distinct reef facies associations occurred both vertically and laterally reflecting changing environmental conditions during the Holocene. Changes in reef facies and the ultimate demise of the Holocene reef probably involved a combination of factors, including response to increased sea-level, coastal flooding and erosion during the Holocene highstand, with associated increase in sedimentation, turbidity and decline in water quality; burial by sediment buildup during the mid-Holocene highstand and detrital progradation during the mid- to late-Holocene regression; and the introduction of alluvial sediment during severe storms and cyclone activity to an already stressed environment.

The contemporary submerged reefs lining the western Exmouth Gulf may represent a mixture of reef ‘turn-ons’ and ‘turn-offs’ (Buddemeier and Hopley, 1988; Kleypas, 1996) at various growth stages, including incipient reefs with coral reef communities that have not yet grown to present sea-level; veneers of non-reef-building coral communities on exposed relict surfaces; or, as this marina transect study has illustrated, reefs that developed earlier in the Holocene and were later turned-off by environmental changes shifting to algal dominated states. The effect of environmental disturbance on coral reefs due to climate change and other anthropogenic stresses may depend on which growth type a particular reef represents. Local activities that may increase disturbances such as increased sedimentation and turbidity from dredging, coastal development and overfishing, must be considered particularly at a time when increased global challenges to coral reef environments may reduce reef resilience.

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5. Communication and Outputs

5.1. Communication Achievements

5.1.1. PhD Theses

Emily Twiggs, PhD Candidate, Supervisor Assoc. Prof. Lindsay Collins, Curtin University – Geomorphology, Sediments and Habitats of Ningaloo. Due for completion in 2011. Forms part of WAMSI Projects 3.4.1 and 3.4.2.

5.1.2. Publications

Journal Articles

Cassata, L., Collins, L.B., 2008. Coral reef communities, habitats, and substrates in and near Sanctuary Zones of Ningaloo Marine Park. Journal of Coastal Research: Vol. 24, No. 1 pp. 139–151.

Twiggs E.J., and Collins L.B. 2010. Development and demise of a fringing coral reef during Holocene environmental change. Marine Geology 275, 20-36.

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Collins, L.B. 2011: Reef Structure. In: David Hopley (ed.) Encyclopedia of Modern Coral Reefs, Springer.

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Reports

Collins L.B. and Twiggs E.J. 2010. Ningaloo Marine Park - Geomorphology and Growth History - Core Study. Final Report, Feb 2010.

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Collins L.B., Twiggs E.J., Tecchiato S., Stevens A. Growth history, geomorphology, surficial sediments and habitats of the Ningaloo Reef. 2008. In: Waples, K (Ed.). Ningaloo Research Progress Report: Discovering Ningaloo - Latest findings and their implications for management. Ningaloo Research Coordinating Committee. Department of Environment and Conservation, WA.

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Twiggs E.J and Collins L.B. 2007. Ningaloo Marine Park Inshore (2A) Geomorphology, Surficial Sediments and Habitat Linkages. WAMSI Node 3 Project 3.4 Progress Report July 2007.

5.1.3. Planned Publications

Twiggs E.J., Collins L.B. 2011 submission to Continental Shelf Research. Sediment facies mapping of the northern Carnarvon Shelf, Western Australia. Submit end March 2011

Twiggs E.J., Collins L.B, Tecchiato S. 2011 planned submission to Marine Geology. Geomorphology, sedimentary environments and habitats of the northern Carnarvon Shelf adjacent to the Ningaloo Reef, Western Australia. Submit end May 2011

Twiggs E.J., Collins L.B., Fitzpatrick, B.M. 2011 planned submission to Journal of Coastal Research/Coral Reefs. Geomorphology and coral community zonation of the northern Ningaloo Reef. submit end July 2011

Potential additional titles may include:

Twiggs E.J., Collins, L.B. 2011 planned submission to Sedimentology. Carbonate assemblages of the northern Carnarvon Shelf, Western Australia.

Twiggs E.J., Collins L.B. . Submission to Marine Geology/Sedimentology. Geomorphology and carbonate sedimentology of the Ningaloo Marine Park.

Twiggs E.J., Collins L.B,. and Colquhoun J. Influence of geophysical variables on the biodiversity of the northern Carnarvon Shelf.

5.1.4. Presentations

Twiggs, E.J. 2010. Geomorphic and sedimentary environments for conserving Ningaloo's biodiversity. WAMSI AMSA Marine Science in WA Show and Tell Symposium 2010. Presentation.

Collins L.B. and Twiggs E.J. 2009. Geomorphology and reef growth History. WAMSI Symposium 2009 Abstract and presentation.

Twiggs E.J., and Collins, L.B. 2009. Development and demise of a fringing coral reef during changing sea-level and environment in the Holocene, eastern Ningaloo Reef, Western Australia. WAMSI Symposium, Exmouth July 2009. Abstract.

Twiggs E.J., and Collins, L.B. 2009. Mapping geomorphology and sedimentary environments for conserving marine biodiversity of the Ningaloo Marine Park. WAMSI Symposium, Exmouth July 2009. Abstract.

Twiggs E.J., and Collins, L.B. Geomorphology sediments and habitats of Ningaloo reef and Shelf. WAMSI Student Symposium 2009. Abstract and presentation.

Twiggs E.J., and Collins, L.B. 2009. Development and demise of a fringing coral reef during changing sea-level and environment in the Holocene, eastern Ningaloo Reef, Western Australia. Consortium for Ocean Geoscientists (COGS), Curtin, 2009.. Poster Presentation

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Twiggs, E.J., and Collins, L.B. 2008. Geomorphology and sedimentary environments of the Ningaloo Marine Park. IGCP 526, Brazil, Nov 2008. Abstract and presentation.

Twiggs, E.J., and Collins, L.B. 2008. Ancestral Foundations and Geomorphology in Conserving Habitats and Communities of the Ningaloo Reef, Western Australia. International Coral Reef Symposium (ICRS) July 2008, Florida. Abstract and poster presentation accepted.

Twiggs, E.J. and Collins, L.B. 2008. Mapping geomorphology and sedimentary environments for conserving marine biodiversity of the Ningaloo Marine Park. 2008 Joint NZMSS and AMSA Marine Science Conference. July 2008, Christchurch NZ. Abstract and presentation.

Twiggs, E.J., and Collins, L.B. 2008. Geomorphology, Surficial Sediments and Habitats of Ningaloo Reef. WAMSI/AMSA Show and Tell, Feb 26th 2008, Fremantle. Presentation.

Collins, L.B. 2008. Ningaloo Reef ancestral morphology and growth history. Second Annual Ningaloo Research Symposium, May 2008. Presentation.

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Twiggs, E.J., and Collins, L.B, 2007. Geomorphology, Surficial Sediments and Habitats of the Continental Shelf and Reef System of Ningaloo. 4th Western Australian State Coastal Conference 30th of October - 4th November 2007. Presentation.

Collins, L.B, 2007. Coral reefs: present day hazards, past responses to climate change, and future issues. 4th Western Australian State Coastal Conference 30th of October – 4th November 2007. Presentation.

Twiggs E,J. and Collins, L.B. 2007. Geomorphology, Sediments and Habitats of Ningaloo Reef, Western Australia. Australian Coral Reef Society Conference (ACRS), Fremantle Oct 2007. Abstract and presentation.

Collins, L.B., Twiggs, E.J., Stevens, A. 2007. Ningaloo reef ancestral morphology: A key to understanding substrates and biodiversity? Australian Coral Reef Society Conference (ACRS), Fremantle Oct 2007. Abstract and presentation.

Twiggs, E,J., and Collins, L.B. 2007. Geomorphology, Sediments and Habitats of Ningaloo Reef. WAMSI Symposium, July 2007. Proceedings abstract.

Collins L.B. 2007. WAMSI Show and Tell, March 2007. Invited delegate and presenter.

Twiggs, E,J. 2006. Geomorphology, Habitats and Surficial Sediments of the Ningaloo Continental Shelf and Reef System: Implications for Biodiversity. INQUA/IGCP 464 field meeting ''Sub-aerially exposed continental shelves since the Middle Pleistocene climatic transition'', 13–18 August 2006, Exmouth, Australia. Abstract and presentation.

Collins, L. B. 2006. INQUA/IGCP 464 field meeting ''Sub-aerially exposed continental shelves since the Middle Pleistocene climatic transition'', 13–18 August 2006, Exmouth, Australia. Abstract and presentation.

Twiggs, E.J. 2005. Evolution, Morphology and Habitats of Ningaloo Reef: Impacts and Resilience. Consortium for Ocean Geosciences (COGS) of Australian Universities Conference, Orpheus Island Research Station, June 25-29 2005. Abstract publication and presentation.

Collins, L.B. 2005. Consortium for Ocean Geosciences (COGS) of Australian Universities Conference, Orpheus Island Research Station, June 25-29 2005. Abstract publication and presentation.

Twiggs, E.J. 2005. Morphology and Habitats of Ningaloo Reef: Impacts and Resilience. 3rd Annual Australian Marine Science Association (AMSA) PhD workshop, Rottnest 2005. Abstract publication and presentation.

5.1.5. Media Presentations

2010

Ningaloo may join World Heritage Listing - Sydney Morning Herald, 06 Jan 2010.
http://news.smh.com.au/breaking-news-national/ningaloo-may-join-world-heritage-list-20100106-ltpj.html

Ningaloo may join World Heritage List - The West Australian, 06 Jan 2010.
http://au.news.yahoo.com/thewest/a/-/national/6649459/ningaloo-may-join-world-heritage-list/

Ningaloo may join World Heritage listing - SBS World News, 06 Jan 2010.
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2009

Coral grief as reef damage grows due to climate change and sea temperatures rising – Herald Sun, 26 Oct 2009. http://www.heraldsun.com.au/travel/coral-grief-as-reef-damage-grows-due-to-climate-change-and-sea-temperatures-rising/story-e6frfhb6-1225791267689

Ningaloo Reef vies for World Heritage Listing - The West Australian Newspaper, 21 Oct 2009. http://asdi.curtin.edu.au/files/Ningaloo%20Reef%20vies%20for%20world%20heritage%20listing.pdf

Reef may get heritage listing nomination - Sydney Morning Herald, 20 Oct 2009. http://news.smh.com.au/breaking-news-national/reef-may-get-heritage-listing-nomination-20091020-h6lj.html

Heritage Listing could protect Ningaloo: Researchers - The West Australian, 20 Oct 2009. http://au.news.yahoo.com/thewest/travel/a/-/travel/6366338/heritage-listing-could-protect-ningaloo-researchers/

Reef may get heritage listing nomination – 9 News, 20 Oct 2009. http://news.ninemsn.com.au/national/878026/reef-may-get-heritage-listing-nomination

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Australian researchers welcome heritage nomination of coral reef – China View, 20 oct 2009. http://news.xinhuanet.com/english/2009-10/20/content_12279307.htm

Young WAMSI scientist monitors changes to Ningaloo – WAMSI website. http://www.wamsi.org.au/news-and-events-news/young-wamsi-scientist-monitors-changes-ningaloo

Ningaloo Heritage Plan lauded – Kalgoorlie Miner, 21 Oct 2009. http://asdi.curtin.edu.au/files/Ningaloo%20heritage%20plan%20lauded.pdf

Ningaloo looks set for World Heritage nomination - Perth now, 20 Oct 2009. http://www.perthnow.com.au/news/western-australia/ningaloo-looks-set-for-world-heritage-nomination/story-e6frg14u-1225788756034

Australia: reef may get heritage listing nomination – Indian Ocean-South East Asian Marine Turtle Memorandum of Understanding, 20 Oct 2009.

http://www.ioseaturtles.org/headline_detail.php?id=1514

Ningaloo will point to change - Ningaloo Research Centre, 2009.
http://nrc.quantuminteractive.com.au/MediaCentre/tabid/67/vw/1/ItemID/2/language/en-US/Default.aspx

Young scientist watching the Ningaloo - Curtin News, 19 Oct 2009 - http://news.curtin.edu.au/curtin-news/news/young-scientist-watching-the-ningaloo

2008

Science Network WA, online article 'WA's 'living laboratory' has global research significance'.
http://www.sciencewa.net.au/index.php?option=com_content&task=view&id=2327&Itemid=587

5.2. Project Outputs

See above in Publications for reports. Data products include excel spreadsheet of core data.

5.3. Data Management

See Appendix 1

Appendix 1 – Data Management

Please answer the following questions about your WAMSI research datasets. If you have other documentation that describes the data you collected please also attach with this spreadsheet or just attach that if it answers all these questions.	WAMSI Project 3.4.1: Reef Morphology and Growth History Eastern Ningaloo Reef (Exmouth Gulf)
What	
What is the title of the study? (e.g. what would like to be the title of the metadata record)	WAMSI Project 3.4.1: Reef Morphology and Growth History – Eastern Ningaloo Reef (Exmouth Gulf) Development and demise of a fringing coral reef during Holocene environmental change, eastern Ningaloo Reef, Western Australia
What would be some key words for searching for this data?	Holocene reef growth; Pleistocene foundations; geomorphology; climate change; Ningaloo Reef; Exmouth Gulf.
What constraints would you place on the data (e.g. legal, usage - purposes that shouldn't use the data)	Research and Management purposes only.
what kind of data will/has been collected (e.g. sp richness, inventory, abundance, density etc)	Core data, reef stratigraphy and identification of biological samples, U-series thermal ionization mass spectrometry (TIMS) dating of coral samples.
Who	
Who did the research? Please list names and the contact details.	Miss Emily Twiggs: E-mail addresses - emily.twiggs@postgrad.curtin.edu.au , emilytwiggs@hotmail.com Associate Professor Lindsay Collins: E-mail address – L.Collins@curtin.edu.au
Who is point of contact in case of questions? Please list their contact details - is there a generic contact that could be used to ensure longivity?	Emily Twiggs. Tel: +61 8 9266 7968; Fax: +61 8 9266 3153. E-mail addresses: emily.twiggs@postgrad.curtin.edu.au, emilytwiggs@hotmail.com (E.J.Twiggs). Postal address: Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia.
Who else should be acknowledged? Any links to journal articles?	The authors wish to thank the Western Australian Marine Science Institution (WAMSI) for funding as part of the Ningaloo Reef Program Project 3.4 and a WAMSI PhD top-up scholarship for ET. We are grateful to Cleve Flottmann (WA Department for Planning and Infrastructure) for allowing access to the cores for this study, and Marie Kospartov (coral), Viviane Testa (coralline algae) and Justin Parker (foraminifera) for help with identification. We would also like to thank Ben Fitzpatrick for shared fieldwork and volunteers for all their assistance. Collection of hyperspectral imagery was funded by BHP-Billiton through the Australian Institute of Marine Science (AIMS). Gratitude is expressed for the comments of Lucien Montaggioni, John T. Wells and an anonymous reviewer which have greatly improved the manuscript. Journal publication link: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6M-4YX7KR9-1&_user=10&_coverDate=09%2F15%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1636439411&_rerunOrigin=scholar.google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5

	=a1600e472ed99b2217e4c995c9fb9139&searchtype=a
Why	
Why was the research done? This is the abstract - a brief summary of the content of the research is required including the research intentions include summary of aims and objectives and use	Reefs lining the western Exmouth Gulf, located at the northern limit of the 300 km long Ningaloo Reef in Western Australia, represent modern incipient coral reefs and veneers of non reef-building coral/algal communities on exposed Pleistocene or 'give-up' Holocene reef surfaces. Acquisition of sixteen cores alongside U-series TIMS dates were used to confirm the nature of the Pleistocene foundation and characterise Holocene reef development. Three calcretised Pleistocene units were identified as 1) the Last Interglacial (MIS 5e) reef directly underlying Holocene units, 2) a mid-Pleistocene (MIS 7?) bioclastic conglomerate unit, and 3) a Pleistocene alluvial fanglomerate. Eight Holocene reef facies (total thickness of 1.8-5.3 m) included coral framework facies (domal, arborescent, mixed, tabulate and encrusting) and detrital facies (carbonate sand, skeletal rubble and alluvial fan deposits). Holocene ages range from 7.93-5.8 ka BP with vertical accretion ranging from 1.46-9.88 mm/yr (avg. 4.11 mm/yr). Highest rates of accretion and thickest accumulation occurred in the most seaward and deepest cores composed of massive coral framestone and coralline algal crusts. A six stage Holocene chronology is proposed, including 1) coastal inundation from 8-8.5 ka BP, 2) initiation 'start-up' from 8-7.5 ka BP, 3) rapid growth 'catch-up' and back-step from 7.5-7 ka BP, 4) rapid aggradational growth 'catch-up' from 7-6.5 ka BP, 5) reef decline 'give-up' and detrital buildup from 6.5-5.8 ka BP, and 6) detrital buildup and progradation from 5.8 ka BP to present. Changes in reef facies and the ultimate demise of the Holocene reef probably involved a combination of increased sea-level, coastal flooding and erosion during the mid-Holocene highstand, with associated increase in sedimentation, turbidity and decline in water quality; burial by sediment buildup during the mid-Holocene highstand and detrital progradation during the mid- to late-Holocene regression; and, the introduction of alluvial sediment during cyclones and other severe storms to an already stressed community. Modern communities have thus shifted from coral-dominated to bored macroalgal pavements. This study shows that integration of reef development processes with response to environmental change can be used to assess future pressures on coral reef ecosystems globally.
How	
How was the research done? (e.g. instrumentation, brief description of procedure)?	Cores were collected by the Department for Planning and Infrastructure during geotechnical surveys for the Exmouth boat Marina in 1995. Access to cores for this study was given by the DPI. Contemporary reef and coastal geomorphology were investigated using hyperspectral remote sensing data collected by HyVista Corporation. Cores were logged for stratigraphy of major reef units including sediment/rock types, boundaries and hiatuses; primary, secondary and associated reef builders; and other physical features such as calcrete horizons and borings. Seventeen coral samples were selected for dating by high-precision U-series thermal ionization mass spectrometry (TIMS) at the University of Queensland (UQ). Vertical accretion rates were obtained using U-series dated material in relation to the thickness of the deposited carbonates.
How often were measurements taken? Were they aggregated into a specific unit of time (e.g. day, multi-day, week, month, multi-month, year, multi-year)? Change to an overview of sampling design with more detail - spatial and	N/A

temporal parameters	
How is the data currently stored, that is what format is the data? (e.g. GIS shapefiles, compressed AVI etc.) Please provide as much information as possible.	Excel spreadsheet containing core data and U-series dating information. Stored on the Curtin Science and Engineering server, back-up hard drives within the Department of Applied Geology, and on IVEC.
When When was the research carried out? When were the start and end dates?	Logging of cores and analysis in 2009. Publication accepted with Marine Geology April 2010.
Where Where was the research done? As a minimum please indicate the 'bounding box' in latitude/longitude (decimal degrees) (e.g. North bound latitude -22.00; West bound longitude 113.00; East bound longitude 114.00; South bound latitude -23.00)	Exmouth marina core sites (North bound latitude -22.00; West bound longitude 113.00; East bound longitude 114.00; South bound latitude -23.00) Broader geomorphic characterisation for Exmouth region (North bound latitude -22.00; West bound longitude 113.00; East bound longitude 114.00; South bound latitude -23.00)
Where are any other related publications/information about the research published - if any? (e.g. url)	Twiggs, E.J. and Collins,L.B. 2010. Development and demise of a fringing coral reef during Holocene environmental change, eastern Ningaloo Reef, Western Australia. Marine Geology 275, 20-36. doi:10.1016/j.margeo.2010.04.004 Journal Publication Link: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6M-4YX7KR9-1&_user=10&_coverDate=09%2F15%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1636439411&_rerunOrigin=scholar.google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=a1600e472ed99b2217e4c995c9fb9139&searchtype=a
Where in the vertical column of the ocean was the research undertaken? (e.g. minimum and maximum depth)	On the seabed and coastal zone to height/depth of +1.5 to ~-10 m.
site names and GPS coordinates	Exmouth Marina core site: -21.957, 114.141 Bundegi Reef: -21.86, 114.165 Mowbowra Creek: -22.001, 114.125 Point Maxwell: -22, 458, 114.226
ACCESS	Excel spreadsheet containing core data and U-series dating information. Stored on the Curtin Science and Engineering server, back-up hard drives within the Department of Applied Geology, and on IVEC

where is raw data stored (full name, file and location	
where are derived/processed data products stored (full name, file and location)	
where are any other related publications/info	
what constraints/restrictions would you place on the data…	Research and Management purposes only.
Supplementary information - Please attach any further information you think would be useful for future researchers	