WAMSI Node 3 Project 3.4

Ningaloo Marine Park – Characterisation of Geomorphology and Sedimentology - Final Report (Summary) June 2011

Compiled by Lindsay B. Collins, Emily J. Twiggs and Sira Tecchiato

Applied Sedimentology and Marine Geoscience Group

Department of Applied Geology Curtin University of Technology, WA

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Project Leader
Professor Lindsay B Collins

Project Team
Emily Twiggs, Sira Tecchiato

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Note the final version of this summary report will be presented as one of the PhD outputs of Emily Twiggs.

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1. Executive Summary

1.1. Background

The representative protection of marine biodiversity relies on an understanding of the ecosystem components that define benthic habitats (Post et al., 2006; Verfaillie et al., 2009). Seafloor habitats include the physical abiotic aspects of the seabed environment (Brown and Collier, 2008; McArthur et al., 2010;) such as geomorphology, sediment composition (texture, mineralogy and constituents), mobility of the substrate, bathymetry, rugosity, the hardness and roughness texture of the seabed and water depth. These physical factors can be significant in describing the distribution of benthic biota and fish distributions over broad geographic regions (Williams and Bax, 2001; Roff et al., 2003; Beaman et al., 2005; Ball et al,. 2006; Post et al., 2006; Verfaillie et al., 2006; Wedding et al., 2008; McArthur et al., 2010; Twiggs et al., 2011). Physical parameters can also be measured much more quickly and across wider areas than biological information, providing rapid assessments for the selection and ongoing monitoring of MPA's (Post et al., 2006; Verfaillie et al., 2009).

The seabed can be primarily defined by its bathymetric and geomorphological characteristics (Brown and Blondel, 2009), and seabed geomorphology determines the long-term stability of the substrate which represents a major control on biological diversity (Freeman and Rogers, 2003). Geomorphic features can also represent a history of climate and sea-level change, may indicate links to coastal groundwater systems (Twiggs et al., 2011), and can give us vital information on oceanographic processes (Ryan et al., 2007; Twiggs et al., 2011). Sedimentology is also one of the most crucial variables as it rules sediment transport processes and is often the missing link for the prediction of soft substrate habitats or macrobenthic communities/species (Verfaille et al., 2006). Migration of sedimentary bedforms indicates active bedload transport and their movement may limit the establishment of communities and pose a threat to established communities by burial (Harris, 1989; Marber and Duarte, 1995; Walker et al., 1996; Daniel et al., 2008).

Full coverage habitat mapping is essential for baseline and monitoring phases for marine conservation (Verfaillie et al., 2006; Brown and Collier, 2008; Ierodiaconou et al., 2010; Robinson et al., 2010), and fisheries management (Wedding et al., 2008). Grab sampling and geomorphic investigations can be used as ground-truthing for remote sensing surveys to characterise the nature of the seabed over the broadscale in terms of surficial sediment facies, geomorphic features, bedforms and infer ecological information in a particular environment (Bale and Kenny, 2005).

The Ningaloo Reef provides an ideal case study to advance baseline understanding of near pristine reef geomorphology, sediment distribution and habitat variability, and establish the current condition of the reef for the evaluation and monitoring of future change. Many coral reefs exhibit distinctive patterns of geomorphic zonation and associated ecological zones in which coral community structure (cover, spatial patterns, diversity and abundance) can be attributed to the interaction of reef processes and the physical environment (water-energy regime and light), and biotic interactions (Stoddard, 1969; Montaggioni and Braithwaite, 2009). During initial habitat mapping of sanctuary zones in the Ningaloo Marine Park (Cassata and Collins, 2008) it was recognised that much of the lagoon substrate and geomorphology, important for shaping modern coral reef habitats, is inherited from an earlier "Tantabiddi" stage of reef growth during the Last Interglacial (ca. 125 ka ago) (Collins et al, 2003, Collins, 2010b). The Carnarvon Shelf, which lies adjacent to the Ningaloo Reef, is atypical of the Australian margin with the narrowest section of shelf and steepest shelf break. Diverse sponge-dominated filter-feeding communities are also strongly influenced by antecedent shelf topography (Cassata and Collins, 2008; Twiggs et al. 2011). An understanding of seabed geomorphology and bedform environments will have a direct bearing on the nature and distribution of substrates and communities, both within the Ningaloo Reef system and on the adjacent shelf.

In this second component of the research in Project 3.4, we aim to provide an understanding of how ancestral features influence present day geomorphic structure of the reef and shelf, the influence of contemporary geomorphic features and sedimentary environments on community distribution, and the processes that have shaped these features. This research presents an interdisciplinary study through the use of a Geographic Information System (GIS) and seabed mapping techniques, using remote-sensing technology, traditional sedimentological sampling and benthic video, and provides an important baseline for future habitat mapping, biodiversity assessments, spatial planning, and fisheries management. The characterisation and mapping of benthic habitats based on physical parameters is central for the ongoing monitoring, management and conservation of the NMP's inshore and offshore resources, particularly during a time of increasing anthropogenic and environmental pressures.

1.2. Methods

Both the inshore and offshore components of this research present an interdisciplinary study through the use of reef coring and dating, remote sensing mapping techniques, GIS interpretation, and ground-truthing data including georeferenced video/photo transects, sediment grabs and rock samples.

1.2.1. Inshore Coral Reef

n 2006 and 2007 four finescale surveys of habitats, coral community structure, surficial sediments, geomorphology and reef fish assemblages (a collaborative effort with UWA under WAMSI Project 3.2) were completed in the shallow inshore areas of the NMP.

For the Cassata and Collins (2008) study, reef zones of the northern Ningaloo were mapped by manually delineating geomorphic and habitat boundaries from aerial photography as polygons in ESRI ArcGIS software. In this continuing study, contemporary reef and coastal geomorphology were investigated using new hyperspectral remote sensing data. 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. Hyperspectral imagery was draped over bathymetry using Global Mapper software (www.globalmapper.com) for 3D visualisation, extraction of bathymetric profiles and slope measurements to allow further characterisation of overall reef structure and detailed geomorphic zonation.

Using diver operated benthic video, specific lagoon habitats were surveyed for the northern Ningaloo Reef at five locations. Locations were identified where combinations of the most commonly encountered geomorphic zones/habitats could be identified from aerial imagery and previous knowledge (outer reef flat, mid-inner reef flat, Inner reef flat/back reef, lagoonal sand flat, lagoonal and inter-reef gutters, lagoonal pavements, lagoonal ridges, lagoonal channels and reef passes; refer to WAMSI Project 3.4 reports and Cassata and Collins, 2008 for further detail). Video transects were supported by digital photo-quadrats to measure coral community structure and variability within these major habitats. Benthic video was analysed using the Australian Institute of Marine Science Automated Video Transect Analysis System (AVTAS) to quantify the percent cover of biophysical habitat variables and images of corals were identified up to species level where possible and growth form.

1.2.2. Offshore Continental Shelf

In April and May 2006/2007 and Jan 2008 the Australian Institute of Marine Science (AIMS), in conjunction with Curtin University, the WA Museum, and UWA, initiated surveys in the NMP to characterize the biodiversity of the deepwater component of the reserves (offshore of the fringing reef) and develop broadscale habitat maps as part of Projects 3.4 and 3.1.1. This offshore component focused on mapping the seafloor with acoustics (multibeam and single beam) and collecting georeferenced towed-video data, sediment grabs and dredged samples to verify acoustic interpretations, and characterise the geomorphic, sedimentary and biological aspects of the seabed within the NMP.

Finescale investigations were undertaken in a section of the northern shelf to develop a robust methodology by which multibeam data could be transformed into classified map products useful for continued research and management of the offshore Ningaloo Reef. ArcGIS layers were produced for multibeam bathymetry and its derivatives (e.g. slope, rugosity), backscatter intensity, geomorphology and interpolated sediment maps. Supervised classification of backscatter (Maximum Likelihood Classification) was undertaken in ENVI software, using ground-truth sediments and supplementary video data as training datasets to create full coverage substrate maps. Classified map products were then draped over multibeam bathymetry using Global Mapper software (www.globalmapper.com) for 3D visualisation, extraction of bathymetric profiles and slope measurements and to allow further characterisation and mapping of geomorphic and sedimentary bedform environments and their associated benthic communities.

Almost 600 surficial sediment samples were collected spanning the entire Ningaloo Marine Park (reef system and shelf) from Bundegi in the north to Red Bluff in the south. A widely spaced systematic grid of samples was used to provide broadscale map coverage. All sediment samples were analysed for grainsize statistics, textural parameters and descriptive terminology (such as fine gravelly sand) using standard classification schemes (see WAMSI 3.4 milestone and final reports for further detail). Interpolated maps of sediment grain size statistics were then developed for the entire NMP. Component analysis was undertaken on representative sediment samples to examine the contribution of different marine organisms to the sediments.

2. Key Findings and Recommendations

2.1. Objectives

The overall aim of 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 main objectives of this component of the research (3.4.2) were to:

- Identify evolutionary characteristics relevant to maintaining marine biodiversity of the reef and shelf;
- Characterise coastal and seabed geomorphology of the reef, including deep reserve and lagoon areas;
- Characterise the surficial sediments of the shallow lagoonal waters and shelf;
- Identify relationships between geomorphology and sediment characteristics and the distribution of benthic habitats and communities.

These objectives are reflected in the following management related questions that were posed:

- What are the key geomorphic features in the NMP and how are they distributed across the park?
- What are the key sediment characteristics and how are they stratified through the park?
- What is the relationship between geomorphology, sediment characteristics and the distribution of benthic habitats and communities?

To approach these questions broadscale investigations were undertaken for the entire NMP and in detail for the northern Ningaloo Reef and shelf, to map and characterise bathymetry and seabed texture, geomorphology (reef and shelf zones/features), sedimentary bedform environments, surficial sediments (physical and biological components) and associated benthic communities. This research was reconnaissance in nature and is by no means a comprehensive study of the whole of the reef tract and continental shelf, but it has provided fundamental information on ancestral, and contemporary geomorphology and sedimentology of the NMP, the oceanographic processes that have contributed to their formation and the influence of physical environments on benthic communities. These relationships may be used to inform our understanding of benthic habitat variability across the whole NMP, and will aid in development of benthic habitat maps central to the ongoing conservation and monitoring of biodiversity at Ningaloo.

2.2. Outcomes – Key Findings

2.2.1. Coral Reef Geomorphology, Sediments and Habitats

2.2.1.1. *Ancestral Controls*

The reef growth history component of WAMSI 3.4 (see summary for Project 3.4.1 in this report, Collins and Twiggs, 2011; Twiggs and Collins 2010, and previous work by Collins et al., 2003) recognised the strong controls of Last Interglacial reef growth on Holocene reef development, and subsequent contemporary geomorphology and zonation. 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. It seems likely that the position of the western reef crest was controlled by the Last Interglacial reef, based on previous coring at Tantabiddi (see Collins et al., 2003). On the eastern Ningaloo Reef, the Holocene initiated on Last Interglacial platform highs and mimicked the topography throughout its development, further influencing available accommodation (space), reef accretion rates, morphology and facies development.

Whilst the influence of Last Interglacial reef substrate provided a regional control on Holocene growth along the length of Ningaloo Reef (Collins et al. 2003), Pleistocene alluvial fans also provided antecedent surfaces for reef colonisation and locally control Holocene reef morphology (Figure 1). Fans built out (prograded) from the coast as sediments were deposited from ephemeral creeks and gorges such as at Yardie Creek during lower sea-levels. Extensive gutters in the reef flat and deep lagoon areas, may also indicate a karst control on reef morphology, with modern growth on collapsed Pleistocene reef limestone (although additional coring across the back reef will be needed to fully confirm this).

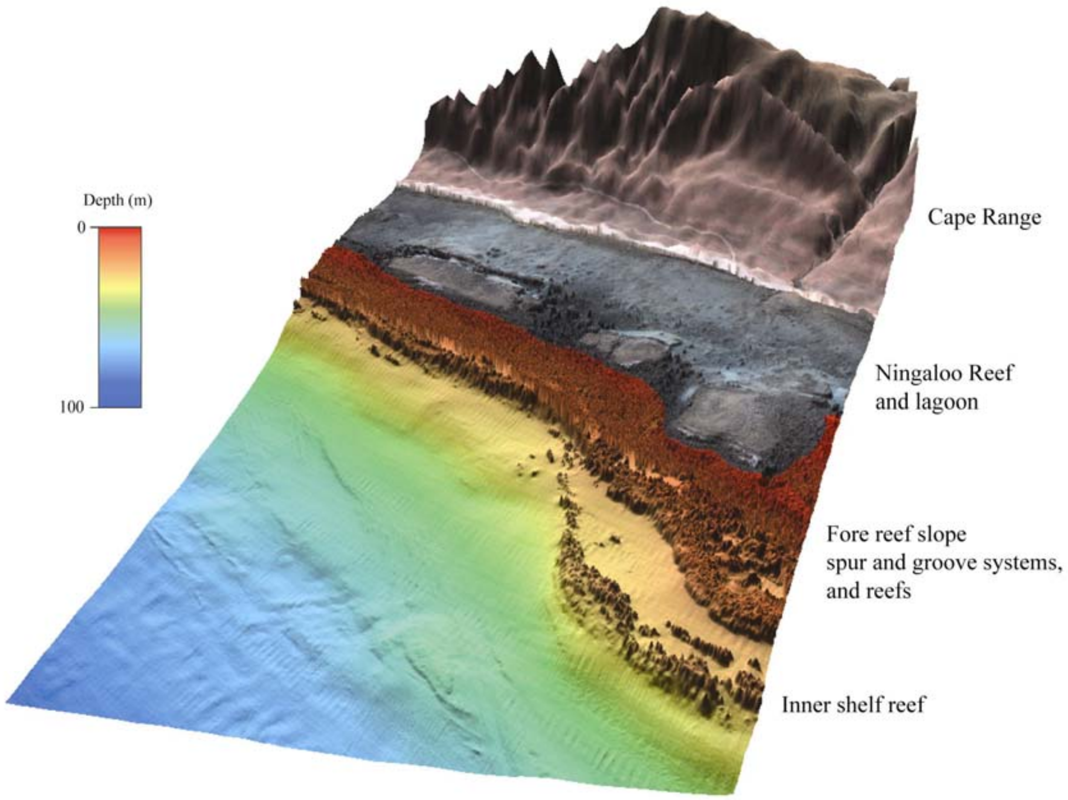

Figure 1. Influence of relict alluvial fan structures on modern reef flat and inner shelf morphology, offshore of Yardie Creek (top right).

In terms of models for fringing reef development, the western Ningaloo Reef most closely resembles the Pleistocene reefal substrate model and Pleistocene alluvial fan substrate model defined by Hopley and Partain (1987) and modified by Smithers et al. (2006), for fringing reefs of the Great Barrier Reef. On the eastern Ningaloo Reef, the reef structure is comparable to early stages of these models. Holocene reef development of the Ningaloo Reef has been strongly influenced by fluctuating sea-level during the Holocene, with the formation of relict reefs ("give-up" reef) and multiple back-stepping spur and groove systems on the fore reef zone, formed as the reef tried to "catch-up" to sea-level during the Holocene transgression. There is the likelihood of a currently prograding (growing seawards) reef flat formed since the Holocene transgression (sea-level fall), ca. 7 ka ago.

Reef structures such as drowned terraces and spur and grooves in the fore reef zone, relict alluvial fans forming reef flats, and channels and gutters in the back reef provide important habitat for a variety of contemporary coral reef communities.

Major storm events and tsunamis have also impacted the Ningaloo coastal zone during the Holocene, with erosion of coastal dunes and pavement, and the deposition of reef material related to major storm/tsunamis washover events. Deposition of reef material almost 1 km inland, includes large *Porites* corals which have yielded U-series dates of 4.5-6 ka in the coastal dunes at Jurabi (Collins et al, 2006). Further detailed research is needed to understand the timing, frequency and severity of these events especially with increased tourism to the coastal zone.

2.2.1.2. *Contemporary reef geomorphology and zonation*

Broad-scale mapping of the reef developed GIS layers for major reef geomorphic zones, and associated major benthos for the northern Ningaloo Marine Park (refer to Cassata and Collins, 2008). This research has provided additional detailed 3D mapping and characterisation of geomorphic zones, associated habitats and coral assemblages.

Many coral reefs exhibit distinctive patterns of geomorphic zonation and associated ecological zones which can be dynamic, changing as reefs grow or conditions change (Smithers et al. 2007). The Ningaloo Reef generally displays distinct geomorphic zonation (Figure 2) with strong correlation between morphology, inherited substrate type, and habitats from the reef front to the shoreline. For a detailed overview of coral reef environments and structures refer to Twiggs and Collins (2011), Collins (2010a, 2010b), Twiggs and Collins (2010), Cassata and Collins (2008), and Collins et al. (2003). A summary of geomorphic zonation and environments is as follows.

1) The ***Fore Reef Slope*** is between 600-900 m wide and drops down to ~35 m. There are distinct spur and groove structures perpendicular to the reef line which have constructional spurs oriented parallel to the dominant swell-wave direction, important for dissipating wave energy. Complex multiple developments of spur and groove are also present occurring as distinct steps down the slope which are more pronounced in shallower parts to ~25 m. Eroded lines of ridges, pinnacles and mounds on the lower slope in ~25-35 m depth, are more discontinuous and rounded in nature with modification by erosional processes. Spur and groove structures have breaks in their morphology consistent with reef passes, but in many areas reef growth continues into the lagoon as a lower relief reef with grooves. In shallower parts of the fore reef (to 10-15 m) spur communities are dominated by encrusting red coralline algae and robust to tabular-branching coral assemblages, with mixtures of domal, arborescent, foliaceous and encrusting corals commonly associated. In depths of

~15-30 m, more delicate foliaceous and encrusting assemblages dominate, which are gradually replaced by a mixed, deeper-water sessile, filter feeding community on the inner shelf. Narrow v-shaped grooves act as conduits for sediment export from the reef to the shelf, and contain rippled sand and coralline algal-encrusted reef rubble.

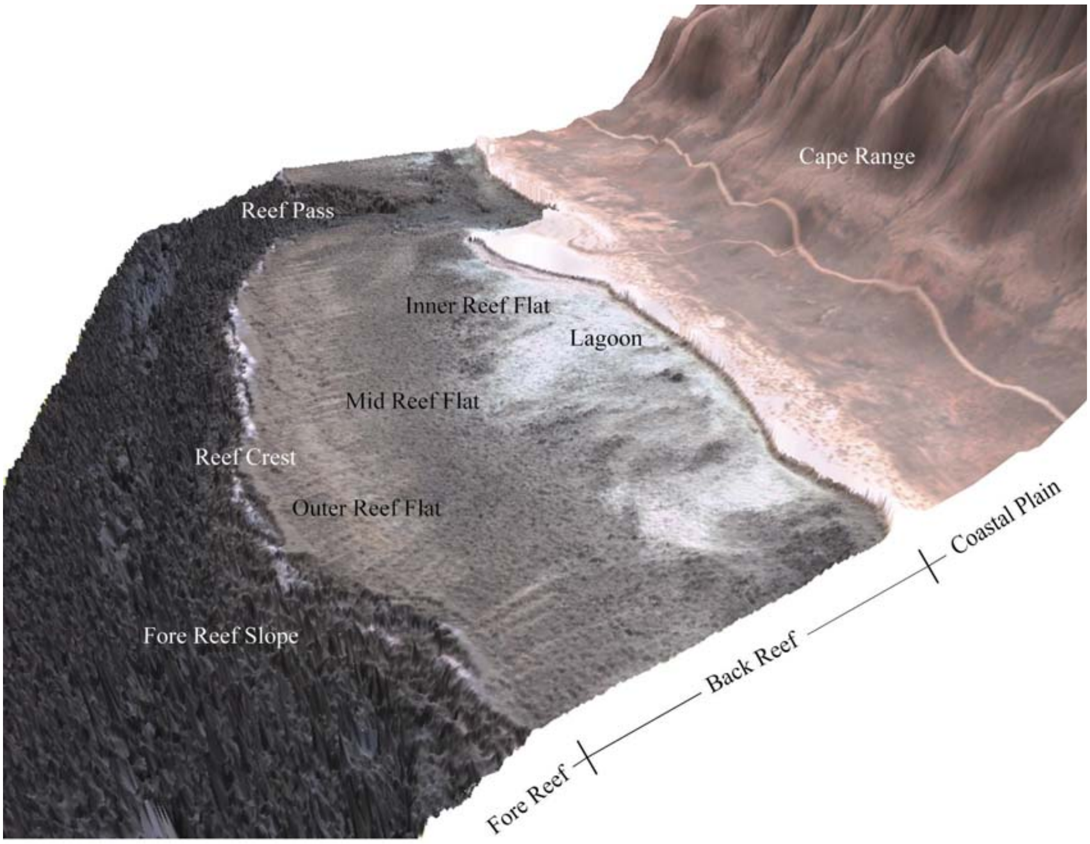

Figure 2. Geomorphic zones of the Ningaloo Reef, Turquoise Bay, Mandu sanctuary zone.

2) The narrow ***Reef Crest*** (up to 50 m width) is the highest energy zone of the reef and forms a linear coralline algal reef rim (intertidal pavement), which may also include small robust-branching and encrusting coral assemblages. In a number of sites a raised reef pavement which lines the crest (up to +1 m), is commonly oyster encrusted and may represent a remnant reef formed during higher sea-level in the Holocene. Large reef blocks up to 4 m diameter are also present along the reef crest and adjacent outer reef flat. These oyster encrusted blocks have been torn from the shallow reef front during high energy storm/cyclone/tsunamis events.

3) The ***Reef Flat*** is generally ~500 m across and up to 1 km width, with shallower parts emergent during low water. The reef flat varies widely in terms of structure and composition depending upon physical factors and gradients (water-energy regime, light and depth) and

biotic interactions (Montaggioni and Braithwaite, 2009). In areas the reef flat continues up to the shoreline without a lagoon being present. Turf algae can be common in all zones living on dead corals and reef pavement, and fleshy macroalgae (commonly *Sargassum*) on bare reef pavements, occur in reef flat zones that have sparse or lack coral communities.

- The very shallow (<1 m) ***Outer Reef Flat*** is located directly landward of the reef crest. Distinct grooves and ridges (aligned coral-algal and rubble zone) are consistent with the spur and grooves on the fore reef slope, attesting to the high energy conditions that continue onto the reef flat. Grooves (surge channels) are dominated by bare reef pavements encrusted by coralline algae with a scattering of small robust-branching coral communities, reef rubble, rhodoliths and coarse gravelly sand veneers. Grooves can broaden to landward penetrating across the entire reef flat into the lagoon, or they can narrow and terminate at the boundary of the mid/inner reef flat where coral communities dominate. Transverse ridges of coral growth are dominated by robust to tabular-branching coral and subordinate domal coral assemblages. Ramparts of reef debris parallel to the reef crest, form from the deposition of material as waves lose energy over the reef flat, and interrupt the aligned coral-algal zone where present. These can also be consolidated forming a hard pavement encrusted by coralline algae which may be suggestive of periodic deposition during high energy storm/cyclone/tsunamis events. Highly barren flats with little coral growth have a high percentage of echinoids and boring organisms.
- The ***Middle Reef Flat*** is characterised by robust-branching and extensive cover of large tabular-branching coral assemblages on reef pavement. The water is slightly deeper (~1-1.5 m) and generally less turbulent than the outer reef flat. Evidence of high intensity storm/cyclone activity is clear in places with damaged and overturned tabulate corals. Small patches of gravelly sands are composed largely of coralline algae, coral and encrusting foraminifera fragments.
- The ***Inner Reef Flat*** (~2-3 m) is characterised by tabular-branching, luxuriant arborescent and domal coral assemblages. Large patches of soft corals can also be found in this zone. These communities often continue into the adjacent back reef lagoon, where reef sand dominates, becoming small patch reefs or scattered coral on sand flats.
- Reef flat gutters/holes occur as breaks in the coral framework which may be inherited from antecedent karst topography. They are much deeper (up to 15 m) and have a sandy floor which is often bioturbated. Coral growth on the steep edges consists mainly of robust-branching, tabular-branching, arborescent and domal coral assemblages. Large domal *Porites* ‘bommies’ are common along the edges and within depressions, associated with more delicate-arborescent forms.

4) The ***Back Reef Lagoon*** is generally ~1-5 m depth, with deeper channels up to ~15 m. Geomorphic features within the lagoon include sand flats, scattered coral/rock in sand, patch

reefs, coral gardens, channels/moats, sand aprons and pavements which provide important habitat for a wide variety of coral and algal communities. Beachrock is also common along the intertidal shoreline and provides an important record of shoreline change.

- Shallow lagoon sand flats can be uncolonised and mobile, coarse, white carbonate sand that is rippled in areas exposed to currents or wave energy, or finer sand that is burrowed by infauna in more protected/deeper lagoon areas.
- Sand flats may also be characterised by scattered coral/rock in unconsolidated sediment, and include a wide variety of communities of arborescent, robust to tabular-branching, domal and foliaceous forms in varying mixes. Soft corals, macroalgae, turf algae and seagrass are also common.
- Patch reefs form isolated, comparatively small reef outcrops of aggregates of generally monotypic coral colonies or large individual coral heads including large domal *Porites* 'bommies', that are surrounded by unconsolidated sediments.
- Coral gardens are expansive areas of low relief coral growth within the lagoon dominated by a variety of forms including robust to tabular-branching, foliaceous, domal and arborescent coral assemblages.
- Lagoon channels/moats are sandy depressions that are deeper areas of the lagoon (to ~15 m). Steep margins with a rocky substrate, form lagoon ridges (associated with breaks in shallow lagoon pavements) and have diverse coral communities dominated by more delicate foliaceous to encrusting assemblages, with associated large domal *Porites* and delicate arborescent forms.
- Sand aprons have formed where high energy across the reef flat, transports reef sediment landwards in aprons spreading out onto the inner reef flat-back reef lagoon area.
- Pavements are flat, low-relief carbonate rock (reef/beachrock), that occur throughout the lagoon but predominantly along the shallow inshore areas contiguous with the rocky shoreline, and adjacent to reef passes. They are dominated by macro/turf algal communities with low cover of corals including small domal and delicate-arborescent assemblages, alongside robust to tabulate-branching and encrusting forms.

5) ***Reef Passes*** are breaks in the Ningaloo Reef that form channels important for circulation of lagoon waters and exchange onto the shelf. Reef passes include a number of different habitats that include macroalgal dominated pavement, reef rubble/rhodoliths with scattered coral/algae, or high cover and diverse mixed coral assemblages of commonly domal, small delicate-arborescent, encrusting, tabular-branching forms, with *Millepora* (fire coral).

2.2.1.3. *Coral Reef Assemblages*

Field observations alongside analysis of video and photo-quadrats has recorded a total of 40 coral genera and 100 species. The most speciose genus is *Acropora* dominating reef flat and shallow fore reef slope habitats. Other common genera include *Montipora*, *Porites*, *Seriatopora* and *Favites*. Different reef zones based purely on coral species composition can be difficult to delineate due to the high degree of species overlap (Montaggioni and Braithwaite, 2009). Montaggioni (2005) identified a number of coral assemblages for Indo-Pacific reefs, based on the dominant growth form in relation to wave exposure and habitat-depth. Cassata and Collins (2008) identified general associations of geomorphic zonation and coral morphology across the Ningaloo back reef, with more robust-delicate forms to landward. Additional work has identified a number of morphological coral assemblages, with dominant species and associated corals, for geomorphic zones and features of the Ningaloo Reef (see Figure 3; for example cross section at Osprey sanctuary zone). Refer to Collins and Twiggs (2011) for detailed information on coral assemblages and species lists associated with particular geomorphic zones.

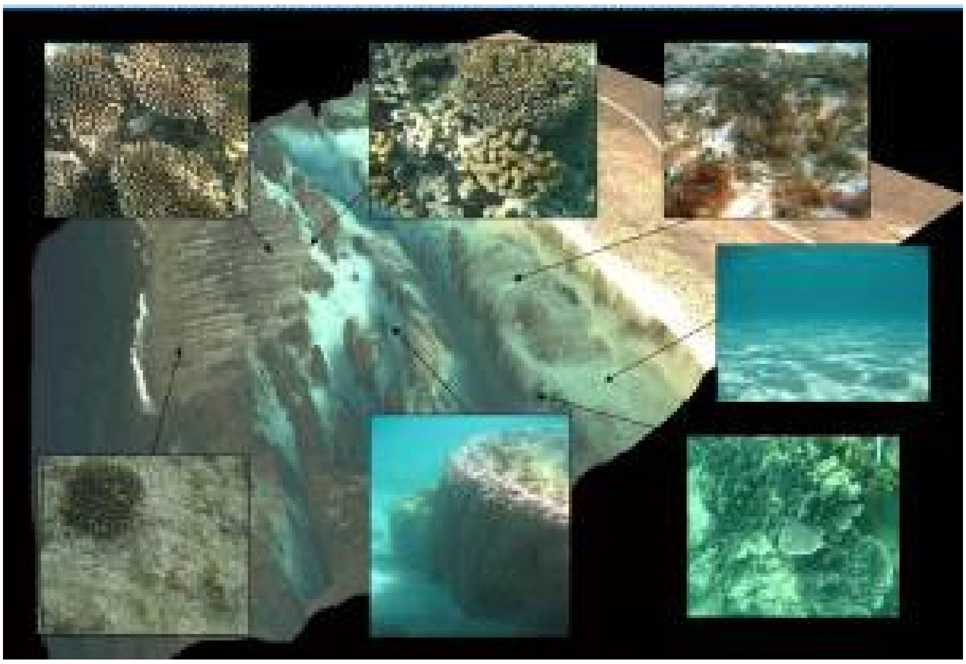

Figure 3: Summary of coral reef habitats of the northern Ningaloo Reef, Osprey sanctuary zone.

Robust-branching coral assemblage is dominated by wave-resistant *Acropora* including sturdy stout-branching, and small digitate, caespitose and corymbose growth morphologies, common in shallow and exposed to semi-exposed settings, preferentially on the mid-upper fore reef slope, the shallow reef crest, and outer-mid reef flat. This assemblage is also found associated with other corals in semi-exposed to protected, inner reef flat-back reef lagoon settings.

Tabular-branching coral assemblage is dominated by *Acropora* with larger corymbose and tabulate (plate) growth morphologies. This assemblage is particularly common in shallow, exposed to semi-exposed settings, including the mid-upper fore reef slope, and the shallow mid-inner reef flat.

Arborescent coral assemblage is dominated by *Acropora* with branching (staghorn) growth morphologies. This assemblage is commonly found in the shallow and semi-exposed to protected inner reef flat and the adjacent back reef lagoon. Non-*Acropora* branching assemblages are dominated by small branching *Seriatopora, Stylophora and Echinopora* which are common in diverse, shallow lagoon coral gardens, and in deeper regions within the back reef, including reef flat gutters, lagoon ridges and reef passes. Branching *Pocillopora* can also be commonly found in shallow lagoon algal pavements.

Domal coral assemblage can be separated into two observed assemblages of massive/head corals. One is dominated by large *Porites* that are frequently found in semi-exposed to protected areas within lagoon sand flats and reef passes, and lining the edges of deeper lagoon channels, reef flat gutters and lagoon ridges. Large flat-topped, truncated microatoll forms are common in shallow lagoon areas. The second assemblage is dominated by small domal Favidae including *Favites*, *Favia* and *Goniastrea,* which can be found in most reef environments.

Foliacious coral assemblage is comprised of laminar platy to frondose forms found in shallow lagoon coral gardens and scattered within shallow lagoon sand flats. Dominant corals include foliciacous *Echinopora* and *Montipora*, commonly associated with small arborescent non-*Acropora* corals. This assemblage is less frequently found in deeper lagoon areas including ridge walls associated with encrusting and domal coral assemblages.

Encrusting coral assemblage is characterised by lamellar, platy-encrusting forms dominated by *Montipora* and commonly found in zones experiencing lower light levels in deeper, semi-exposed to sheltered parts of the fore reef slope (~20-30 m) and sheltered settings in deeper lagoon areas including lagoon ridge walls. This assemblage can also be found in highly agitated waters of the reef crest and outer reef flat zones.

Mixed coral assemblages of the above can be found in a variety of settings on the fore reef slope, reef flat and back reef lagoon.

In addition to coral assemblages, a common carbonate-producing assemblage on the fore reef, reef crest and outer reef flat zones, includes the ***Coralline-algal assemblage***, forming crusts on the reef framework, and associated with encrusting foraminifera including *Homotrema*, surpulid worms and boring vermetid gastropods, bryozoans and sponges.

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. Modern coral reef communities are prolific on the shallow inshore reef at Bundegi in the northwest Exmouth Gulf, and include thickets of arborescent and caespitose *Acropora* and *Pocillopora*, and associated encrusting to foliose *Montipora*; mixed communities with arborescent, large tabulate *Acropora*, small corymbose *Acropora*, minor encrusting to foliose *Montipora*, small domal Favids (*Favites* and *Favia*), and submassive *Millepora*; and communities dominated by tabulate and corymbose *Acropora*. 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.

2.2.2. Continental Shelf Geomorphology, Sedimentary Environments and Habitats

Analysis of multibeam acoustics combined with sedimentary grab and video data, has enabled the characterisation of shelf geomorphology, sedimentary facies, seabed texture and suitability to support significant biota from the fore reef slope of the Ningaloo Reef to the edge of the continental shelf. Geomorphic features represent a complex geologic framework of Pleistocene limestone bedrock mantled with relict Pleistocene, and Holocene carbonate sediments, and coral reef growth. 3D bathymetry and seabed texture maps have been used to identify key geomorphic features and physical processes that influence deeper filter-feeding and shallow coral reef communities.

The continental shelf in the northern Ningaloo Marine Park is typical of a gently sloping distally steepened carbonate shelf lying adjacent to an extensive fringing reef system. The shelf is atypical of the WA margin with the narrowest section of shelf and steepest shelf break, adjacent to the Cape Range Peninsula. There is a distinct latitudinal variation in shelf width and bathymetry. In the north, the shelf is narrow and gentle with a marked change in gradient at the shelf break (~125-130 m), dropping steeply to depths of 1000 m within only ~6-7.5 km offshore. South of Point Cloates, there is a marked transition in bathymetry with a gentler and wider shelf to the south. The Ningaloo Marine Park incorporates depths of up to ~110 m in the north and thus the majority of the continental shelf, and only up to 50-60 m in the south with only the inner-mid continental shelf represented.

A detailed study for the northern shelf (Osprey to Mandu), has identified distinct geomorphic zones based on bathymetry and distinct geomorphic/sedimentary features (reefs, platforms, ridges, bedforms, extensive sand flats and submarine fans), including: a seaward fore reef slope with base at ~35-40 m depth; an inner shelf zone between 35-60 m; a wide, flat middle shelf sand plain in 60-80 m; outer shelf in 80-125 m; and a shelf break ridge and deep-sea canyon heads at 125 m.

There is a strong association between geomorphology and benthic habitats (see Figure 4 for summary x-section) with communities taking advantage of the availability of Pleistocene substrates and gravelly sediments. The hardbottom is mainly composed of a fossilised limestone reef surface, karstified in places due to glacial lowstand subaerial exposure. In the shallow fore-reef slope, there is a thin veneer of Holocene (<10 ka, ka=1000 yr) coralgal growth on multiple back-stepping spur and grooves structures. Modern growth is largely determined by the antecedent Last Interglacial (LI, ca. 125 ka) topography (Collins et al., 2003), and late-Pleistocene relict alluvial fan structures, that would have prograded on to the shelf during lower sea-levels (refer also to Figure 1). Between 35-40 m depth, even where hard substrates are still available, hard corals rapidly disappear, gradually replaced by a mixed, deep-water, sessile filter feeding community. This transition, between the base of the fore reef slope and the inner shelf reef platform, is characterised by reef and rhodolith gravel that supply the hard substrate for a diverse mixed filter-feeding community dominated by crinoids, sponges, gorgonians, sea whips, soft corals, turf algae, macroalgae, bryozoans and *Halimeda*, with minor ascidians and sea pens. On the inner-mid shelf, submarine fans formed from the offshore flushing of lagoon sediments through reef passes, complicate this pattern locally. Rippled sands, with no epibenthos, are commonly associated with fans. Extensive linear ribbon dunes and scours and 'large-very large' bedforms on the mid to outer shelf, indicate a complex interaction of lagoon and slope currents, the wind-driven Ningaloo Current, and the southerly oceanic Leeuwin Current. Communities of sponges, crinoids, bryozoans, soft corals, sea pens and hydroids are patchy in these sandy regions with higher abundance associated with exposed substrates and gravels. Below wave-dominated processes, bioturbation is evident from echinoderm feeding traces, polychaetes and burrowing fish, and a diverse infauna has reworked the sediments to build mounds and burrows. Fields of large gravel mounds occur in depths of ~95 m with basal diameters of up to 20 m, and may indicate conduits to coastal groundwater and paleo-channel sites (refer to WAMSI Project 3.10 final report). A number of ridges and lines of pinnacles have been identified at various depths with prominent and extensive systems on the mid-outer shelf (~70-125 m). Their lengths range from hundreds of metres to tens of kms with widths up to tens of metres, creating an uneven bottom with up to several metres relief. These features may represent drowned back-stepping reef growth and/or paleo-shoreline erosion, reflecting a complex history of fluctuating sea-level. The Last Glacial (~20 ka) shoreline has been identified at the 125 m depth contour. Ridges are colonised by high cover of exotic sponge, gorgonian and bryozoan "gardens", some of which are likely to be new species (refer to WAMSI 3.1.1). Diversity is particularly high in areas adjacent to the continental slope canyons which bring nutrient rich, cold-water upwelling to the shelf edge; ideal conditions for cool-water carbonate production.

A more complex history exists at in the Point Cloates region, where paleo-stillstand escarpments and shorelines, and very high-relief stepwise fossil reefs and pinnacles, support a diverse coralgal and sponge community. South of Point Cloates there is a marked transition in bathymetry with a gentler and wider shelf to the south. Rhodolith and sandy habitats are common in the southern part of the Marine Park. An offshore sinuous ridge system at Red Bluff, at the southern end of Marine Park, again provides the hard substrate for a diverse sponge, soft coral and bryozoan community.

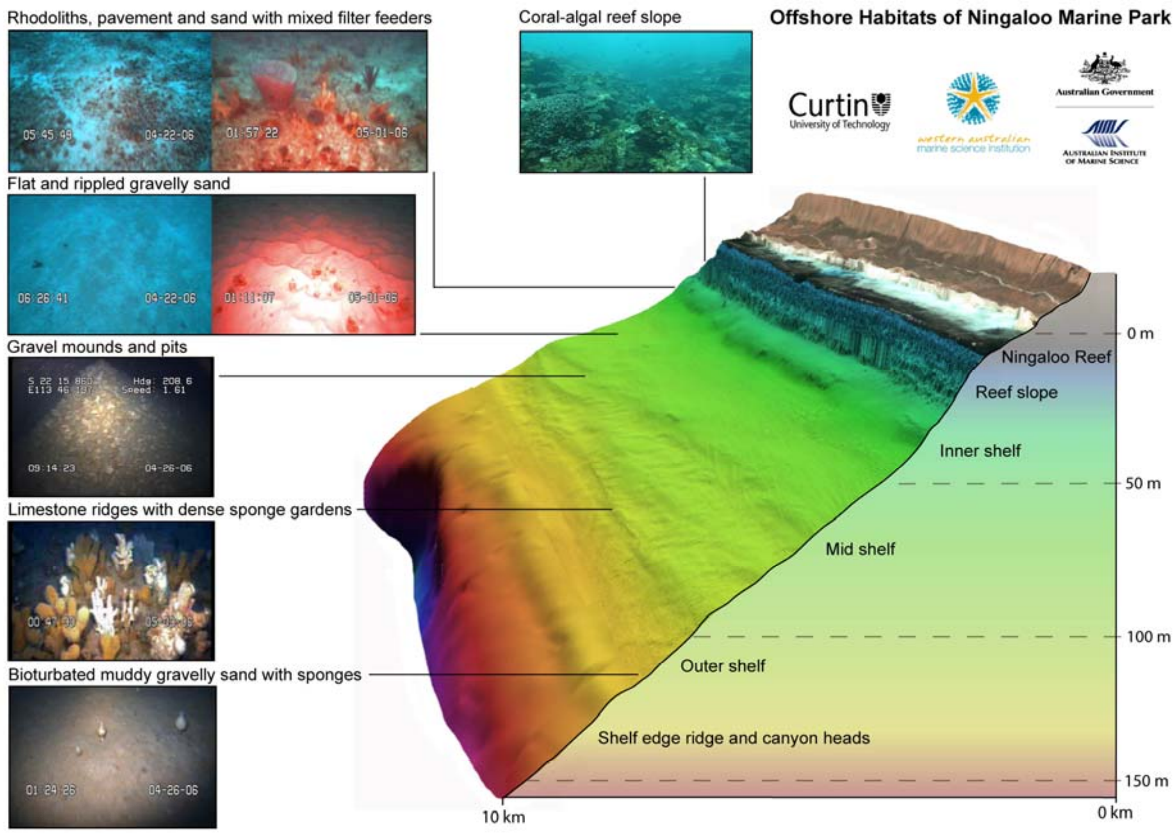

Figure 4: Geomorphology and summary of cross shelf habitats of the northern Ningaloo shelf, Mandu.

Identification of sedimentary bedforms has allowed the characterisation of sediment transport pathways and oceanographic processes on the northern Ningaloo shelf. On the mid shelf, complex dunes including barchans indicate the presence of strong currents down the reef slope and onto the shelf. Large submarine fans indicate the flushing of lagoon waters through reef passes onto the inner-mid shelf. There is a zone of interaction at around 45-65 m between these processes and the wind-driven, north-easterly Ningaloo Current which dominates the mid shelf forming linear ribbon dunes and scours. Interaction between the Ningaloo and the oceanic

Leeuwin Current has been identified in ~75-95 m on the outer shelf, with the south-westerly Leeuwin Current responsible for formation of ‘very large’ bedforms on the outer shelf.

2.2.3. Mapping Seabed Sediment Textures

The distribution of sediment texture has been mapped for the entire Marine Park (Figure 5). Hotspots of high biodiverse seabed habitats correlate well with hard substrates and more gravelly/coarse sandy sediments.

Textural analysis of sediments has also identified sub-parallel belts across the narrow, northern shelf. Rhodolith gravel-bearing sediments dominate the inner shelf, which is characterized by highly rugose ridges, pavements and rhodolith beds, and strong currents preventing continuous sediment cover. Sand-rich sediments occur across the entire shelf with higher percentages on the mid shelf where ripples and dunes systems are common, and on the comparatively stable bioturbated outer shelf. Carbonate mud increases on the outer shelf and in the study area does not exceed ~20%. The mean grain size also illustrates a general decrease across the shelf with depth. The entire shelf is dominated by poorly sorted sediments. Localized areas of very well sorted rhodolith gravels occur on the mid shelf, and zones of moderately to moderately well sorted sediments occur on the inner-mid shelf associated with submarine fan features bringing lagoon sands onto the shelf. Sandy sediments are high in calcium carbonate ($CaCO_3$) content of between 74-92.5%.

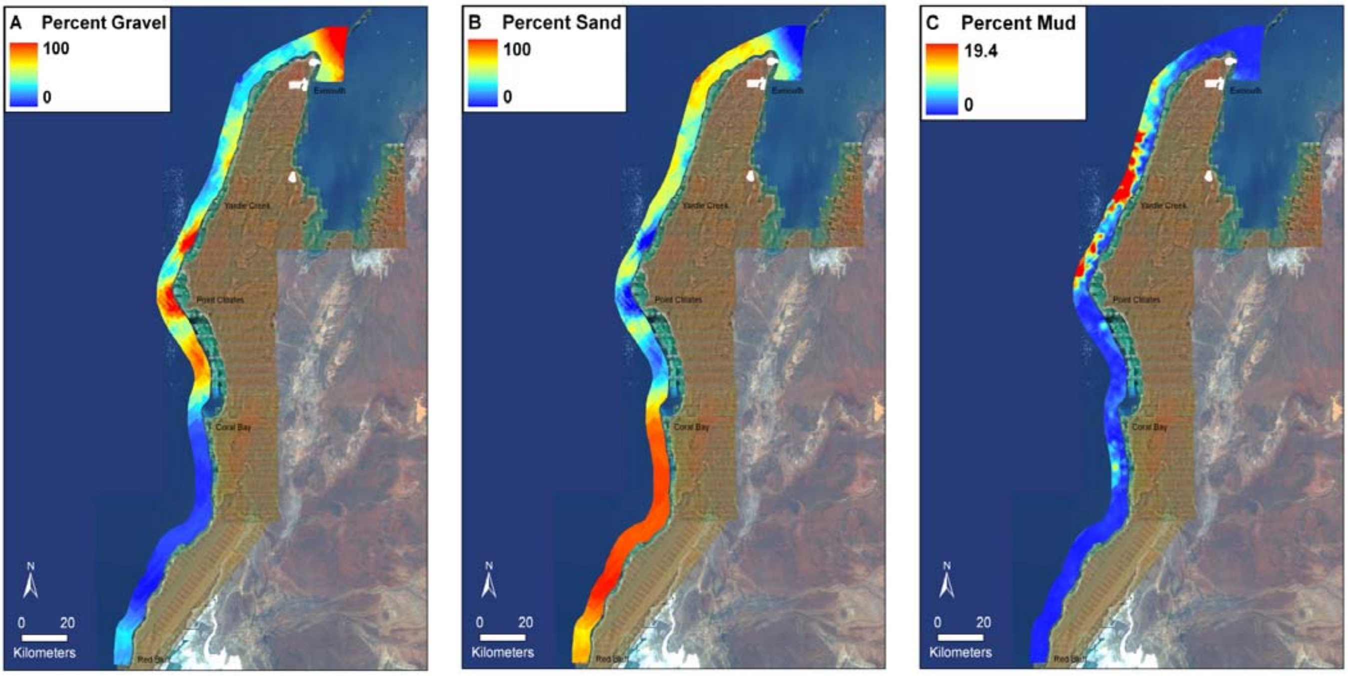

Figure 5: a-c) Sediment grainsize (% gravel, sand and mud) for the Ningaloo Marine Park.

Multibeam backscatter reveals distinct sub-parallel bands of variable backscatter strength related to changes in seabed texture and geomorphic features across the shelf. The classification of multibeam backscatter into sediment/substrate maps is extremely useful when describing the composition of geomorphic and sedimentary features on the shelf and their associated habitats. There is a strong positive linear correlation between mean grainsize and mean backscatter intensity values with the coarsest sediments having the highest mean backscatter, and the finest sediments having the lowest. The strong linear relationship between mean grain size and backscatter intensity allows the extraction of mean grain size values directly from backscatter, providing a complete seafloor coverage map of predicted mean grain size for the shelf. There is also a positive correlation between sediment class (hardbottom/gravel, sandy gravel, gravelly sand, slightly gravelly sand, gravelly muddy sand and slightly gravelly muddy sand) and mean backscatter values on the shelf, allowing classification of the backscatter using additional video observations, into a more meaningful substrate/sediment classification for the shelf.

2.2.4. Sediment components of the Ningaloo Reef and Shelf

Ningaloo Reef lies in a latitudinal transition zone of carbonate-producing communities where both photozoan-reef (warm-water/low nutrient) and heterozoan-carbonate ramp (cool-water/elevated nutrient) producers are found. The study of this unique, near-pristine system provides one of the best analogues for predicting the response of shallow-water carbonates under environmental change.

The carbonate-depositional environment provides a complete range of modern shallow warm-cool water carbonate sedimentary facies across the shelf, with fragments made up of corals (hard and soft), coralline red algae, Halimeda, benthic foraminifera, molluscs, bryozoans, echinoids, and planktic foraminifera. Sedimentary grains are almost wholly biogenic in origin and palimpsest, providing a record of older relict and reworked grains mixed with modern skeletal fragments. In the back reef the sediments are dominated by coral, red algae and molluscan fragments. The carbonate material on the shelf is dominated by mixes of red algae, molluscs, foraminifera and bryozoan fragments. There is a transition of palimpsest sediments across the shelf from modern reef and inner shelf to relict offshore, with a large proportion of mid-outer shelf sediments inherited from late-Pleistocene deposition. This is confirmed by the colour of the sediments with white-yellow-grey (no oxidation) modern sediment facies dominating the reef/inner shelf and orange-brown (oxidised during sub-aerial exposure) sediments on the mid-outer shelf. The sediments have assumed the character of the benthos and become a proxy for habitats that produced them.

Depth consistent sediment facies can be recognised across the shelf and latitudinally, based on component composition and grain size characteristics. Inner shelf sediments are dominated by; hardground/rhodolith beds and coralline red algal gravelly sands; modern skeletal rippled sands transported in submarine fans adjacent to reef passes; modern skeletal gravelly shelf sands dominated by a mixture of coral, red algae, molluscan, foraminiferal and bryozoan components; and modern seagrass/sublittoral fine sands in areas adjacent to lagoonal seagrass meadows (Cloates region). Grains composing whole skeletons or fragments, and gravel sized clasts are heavily encrusted by coralline algae. Middle shelf sediment is dominated by foraminiferal dominated stranded (Holocene) and relict late-Pleistocene skeletal sands. Subphotic sediments on the outer shelf and upper slope are a mixture of modern cool-water, poorly sorted, bryozoan/molluscan dominated gravelly muddy sands with small benthic and planktonic foraminifera, sponge spicules and minor brachiopods. Relict grains again are common. Sediments adjacent to ridges on the mid to outer shelf are highly weathered and relict in nature.

2.2.5. Summary

Geological and sedimentological data were consolidated into a Geographic Information System (GIS) to aid in the production of geomorphic, sedimentary facies and benthic habitat maps of the Ningaloo Reef and adjacent continental shelf, within the Ningaloo Marine Park. An understanding of habitats and the production of maps will provide stakeholders, managers, regulators and policy makers with crucial georeferenced information that will aid in the conservation, preservation and sustainable use of the NMP environment and its values. This research has established a baseline understanding of the geomorphology and sediment distribution in the shallow inshore and deeper offshore waters of the NMP, with an understanding of their influence on the spatial distribution of benthic habitats and communities. The characterisations determined at this scale will improve our understanding of benthic habitat variability across the NMP and provide a baseline for additional habitat studies.

2.3. Implications for Management

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 3.4.2 has focused on the provision of baseline information, it links closely to the biodiversity projects within Node 3 and provides a basis for further generation of management oriented research.

This study integrating geoscientific and biodiversity assessments of the inshore coral reef system and offshore continental shelf, has provided an understanding of the growth history, geomorphic and sedimentary evolution, and associated biological communities. This provides a baseline for further research and monitoring, enabling natural resource management to adapt management strategies of the reserves accordingly. Specific recommendations as they relate to scenarios and management strategies are detailed below.

2.3.1. Management frameworks

The rise in importance of mapping benthic marine environments to inform management of the world's marine biodiversity, has been driven by a general shift from predominantly species-based management strategies to an ecosystem (or spatial) based approach that incorporates marine protected areas (Heap and Harris, 2011). This research has improved our understanding of the geomorphology and sedimentology of the inshore and offshore components of the reserves and will contribute to the identification, classification and management of representative coastal and seabed habitats. This will provide management with the basis for future planning and zoning assessments based on geomorphic features that support specific benthic community and fish assemblages requiring protection. For example shelf features including ridges, rhodolith beds and gravelly sediments have been identified as important sites for highly biodiverse filter-feeding communities dominated by sponges, bryozoans and soft corals. Areas not currently represented in the Marine Park sanctuary zones, including shelf edge ridges that provided some of the most biodiverse regions of the shelf, need further protection. Identifying physical and biological surrogates for many benthic marine organisms is essential for the future of habitat mapping and improving the accuracy of predicting marine biodiversity (Heap and Harris, 2011). Recommendations for future management include expanding this baseline research to provide further understanding of physical habitat and biological interactions.

Reef geomorphology and shelf features such as extensive ridge systems, document sea-level history and growth/erosion on the shelf which can provide an important analogue for climate change assessments (Beaman et al., 2008, refer also to WAMSI Project 3.4.1). This research has also identified sites along the Ningaloo Reef tract and along the coastal dune system that have been subject to high intensity storm/tsunamis events. With predictions of greater intensity of severe storms/cyclones 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 and tourism nodes 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. Recommendations for future management would include supporting further investigations of the paleohistories of major storm occurrence and tsunamis impacts along the coastline, to identify sites of elevated vulnerability to these events.

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. Impacts associated with predicted rises in sea-level and intensity of storm/cyclone events, including coastal wave energy, coastal sediment transport, changes in geomorphic features and 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 so that Marine Park management can be adapted accordingly. Increases in sea-level and intensity of storms/cyclones will also bring potential impacts on reef communities. 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. Coral shingle formed from the physical destruction of coral is an important contributor to many geomorphological features (e.g. 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).

The complete range of modern shallow warm-cool water carbonate sedimentary facies has been identified across the shelf. Recommendations for further characterisation of this unique, near-pristine system may provide one of the best analogues for predicting the response of shallow-water carbonates under environmental change, essential for managing future climate change impacts.

Full coverage GIS based maps produced during this research, are essential for baseline and monitoring phases for marine conservation, fisheries management and important for planning future management activities including protecting key biodiversity. The mapping of physical environments (geomorphology, sediments and seabed texture) into a GIS system has facilitated the identification of underlying geomorphic features and sedimentary environments, important for habitats and beach development, that can be used to highlight vulnerable areas requiring additional protection with increasing human pressures (e.g. important back reef habitats, effect on turtle nesting beaches). Increasing the resilience of 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.

2.3.3. Education

Information for public education programs, regarding the importance of underlying physical features and their control on habitat type and distribution and communities, can be generated from research findings using cross-referenced outcomes, public presentations and suitable onsite signage. For example, this project has developed signage for tourism education of cross shelf habitats which is located at Oyster Stacks on the western Ningaloo coastline (refer to Figure 4). 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. Surveillance and Enforcement

Identification and mapping of physical features can be used for planning compliance and surveillance activities, with surveillance effort focusing on areas vulnerable to human use or areas of high significance. As tourism increases greater resources for surveillance and enforcement will probably be necessary.

2.3.5. Research and Monitoring

Within the constraints of a limited budget significant findings have been made on the geomorphology, sedimentology and habitats of the Ningaloo reef system and adjacent shelf providing a baseline for future research and reference sites for long term monitoring. 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 could include the following:

- Continued research utilising data already collected as part of 3.4.2 that was out of the current scope and budget. This includes:
  - Further detailed characterisation and mapping of biological assemblages within carbonate sediments of the Ningaloo Reef and shelf. This is particularly important for providing a baseline prior to impacts on carbonate secreting species predicted during environmental change.
  - Detailed characterisation of biological components including bryozoans, molluscs, foraminifera, coralline algae.
  - Dating of grains to determine the evolution of assemblages during past environmental change.
- Continued collaborations with 3.1.1 partners using existing datasets to:
  - Investigate the use of geophysical surrogates for predictive mapping, and conservation and monitoring of marine biodiversity.
- Additional investigations into the links between geomorphic features identified on the shelf (gravel mounds and pits) and the coastal groundwater system.
- Dredging and coring projects to establish the formation of offshore features such as relict reefs and ridges that are currently important habitats for diverse filter-feeding communities. Identification and dating of relict features such as paleo-shorelines and reefs may provide an analogue for future climate change scenarios.
- Additional community assessments in different geomorphic settings across the entire reef and shelf.
- Monitoring of modern communities for change - using Project 3.4.2 work as a baseline.
- Understanding and ongoing monitoring of sediment budgets of the Ningaloo Reef system and shelf and links to landforms and processes. This is particularly important to understand due to the dynamic nature of sedimentary environments and the influence on biological communities.
- Understanding the processes involved in the formation of sedimentary bedform environments.
- Identification of sites for conservation management based on geomorphological features.

- The significance of spatial variations in geomorphological sensitivity and vulnerability to the effective management of critical organisms and habitats.
- Understanding of the timing of major storm/tsunamis events along the Ningaloo coastline.
- Establishment of a marine and terrestrial GIS of the whole system for research, mapping, land use planning, monitoring and management.

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.

2.4. References

Bale, A.J., Kenny, A.J. 2005. Chapter 2: Sediment Analysis and Seabed Characterisation. In: Methods for the Study of Marine Benthos. 3rd Edition (Ed. A. Eleftheriou and A. McIntyre), Blackwell Publishing, pp. 43-86.

Ball, D., Blake, S. Plummer, A., 2006. Review of Marine Habitat Classification Systems. Parks Victoria Technical Series No. 26, 50 p.

Beaman, R.J. Daniell, J.J., Harris, P.T. 2005. Geology-benthos relationships on a temperate rocky bank, eastern Bass Strait, Australia. Marine and Freshwater Research 56: 943-958.

Beaman, R,J, Webster, J.M., Wust, R.A.J., 2008. New evidence for drowned shelf edge reefs in the Great Barrier Reef, Australia. Marine Geology 247:17–34.

Brown C.J., and Blondel, P., 2009. Developments in the application of multibeam sonar backscatter for seafloor habitat mapping. Applied Acoustics 70 (10): 1242-1247.

Brown C.J., and Collier J.S., 2008. Mapping benthic habitat in regions of gradational substrata: An automated approach utilising geophysical, geological, and biological relationships. Estuarine, Coastal and Shelf Science 78: 203-214.

Cassata, L. and Collins, L.B. 2008. Coral reef communities, habitats, and substrates in and near sanctuary zones of Ningaloo Marine Park. Journal of Coastal Research, 24(1): 139–151.

Collins, L.B., Zhu, Z.R., Wyrwoll, K.H., Eisenhauer, A., 2003. Late Quaternary structure and development of the northern Ningaloo Reef, Australia. Sedimentary Geology 159: 81-94.

Collins L.B., Zhu Z.R., McNamara K.J., Wood, D., 2006. Evolution of Tertiary to Quaternary Carbonates of the Cape Range Region and Ningaloo Reef, Northwest Australia. Field Guide. Department of Applied Geology, Curtin University.

Collins, L.B., 2010a. Reef Structures. In Encyclopedia of Coral Reefs, Ed D. Hopley.

Collins L.B., 2010b, 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. (Rick), eds., Cenozoic Carbonate Systems of Australasia: Society for Sedimentary Geology, Special Publication 95.

Collins, L.B., and Twiggs, E.J., 2011. Ningaloo Marine Park - Reef Morphology and Growth History. Final Report February 2011, WAMSI Project 3.4.1. Department of Applied Geology, Curtin University, produced for the Western Australian Marine Science Institution (WAMSI).

CSIRO, 2007. Climate Change in Australia: Technical Report 2007, Commonwealth Scientific and Industrial Research Organisation, Canberra.

Daniel J.J., Harris, P.T., Hughes, M.G., Herner, M., Heap, A., 2008. The potential impact of bedform migration on seagrass communities in Torres Strait, northern Australia. Continental Shelf Research 2: 2188-2202.

Freeman, S.M., Rogers, S.I., 2003. A new analytical approach to the characterisation of macro-epibenthic habitats: linking species to the environment. Estuarine Coastal and Shelf Science., 26: 1258-1280.

Harris, P.T., 1989. Sand dune movement under tidal and wind-driven currents in a shallow marine environment: Adolphus Channel, northeastern Australia. Continental Shelf Research 9: 981-1002.

Heap, A.D., and Harris, P.T., 2011. Geological and biological mapping and characterisation of benthic marine environments-Introduction to the special issue. Continental Shelf Research 31 (2): S1-S3.

Hopley, D., Partain, B., 1987. The structure and development of fringing reefs off the Great Barrier Reef Province. Fringing Reef Workshop: Science, Industry and Management (Magnetic Island), pp. 13–33.

Ierodiaconou, D. Monk J., Rattray A., Laurenson L., Versace. V.L. 2010. Comparison of automated classification techniques for predicting benthic biological communities using hydroacoustics and video observations. Continental Shelf Research 31 (2): S28-S38.

Marba, N., Duarte, C.M., 1995. Coupling of seagrass (Cymodocea nodosa) patch dynamics to subaqueous dune migration. Journal of Ecology 83, 381–389.

McArthur, M.A., Brooke, B.P., Przelawski, R., Ryan, D.A., Lucieer, V.L., Nichol, S., McCallum, A.W., Mellin, C., Cresswell, I.D., Radke, L.C., 2009. On the use of abiotic surrogates to describe marine benthic biodiversity., Estarine, Coastal and Shelf Science 88: 21-32.

Montaggioni, L.F., 2005. History of Indo-Pacific coral reef systems since the last glaciation: development patterns and controlling factors. Earth-Science Reviews 71 (1–2), 1–75.

Montaggioni, L.F., and Braithwaite, C.J.R., 2009. Quaternary Coral Reef Systems: History, Development Processes and Controlling Factors. Developments in Marine Geology 5. Elsevier, Amsterdam, 532 p.

Post A.L., Wassenberg T.J., Passlow V. 2006. Physical surrogates for macrofaunal distribution and abundance in a tropical gulf. Marine and Freshwater Research 75, 469-483.

Robinson, K.A., Ramsay, K., Lindenbaum, C., Frost,N., Moore, J., Wright, A.P., Petrey, D., 2010. Predicting the distribution of seabed biotopes in the southern Irish Sea. Continental Shelf Research 31 (2): S120-S131.

Roff, J.C., Taylor, M.E., Laughren, J. 2003. Geophysical approaches to the classification, delineation and monitoring of marine habitats and their communities. Aquatic Conservation: Marine and Freshwater Ecosystems, 13: 77-90.

Ryan, D.A., Brooke, B.P., Bostock, H.C., Radke, L.C., Siwabessy, P.J.W., Margvelashvili, N., Skene, D., 2007. Bedload sediment transport dynamics in a macrotidal embayment, and implications for export to the southern Great Barrier Reef shelf. Marine Geology 240: 197-215.

Smithers, S.G., Hopley, D., Parnell, K.E., 2006. Fringing and nearshore corals reefs of the Great Barrier Reef: episodic Holocene development and future prospects. Journal of Coastal Research 22 (1), 175–187.

Smithers, S.G., Harvey, N., Hopley, D., Woodroffe, C.D., 2007. Vulnerability of geomorphological features in the Great Barrier Reef to climate change. In: Johnson, J.E.,Marshall, P.A. (Eds.), Climate Change and the Great Barrier Reef. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, pp. 667–716.

Stoddard, D.R. 1969. Ecology and morphology of recent coral reefs. Biological Reviews of the Cambridge Philosophical Society 44: 433-498.

Twiggs, E.J., Collins, L.B., Tecchiato, S., 2011. Ningaloo Marine Park – Characterisation of Geomorphology and Sedimentology. Final Report 2011, WAMSI Project 3.4.2. Department of Applied Geology, Curtin University, produced for the Western Australian Marine Science Institution (WAMSI).

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.

Verfaillie, E., Van Lancker, V., Van Meirvenne, M., 2006. Multivariate geostatistics for the predictive modelling of the surficial sand distribution in shelf seas. Continental Shelf Research 26: 2454-2468.

Verfaillie, E., Degraer, S., Schelfaut, K., Willems, W., Van Lancker, V., 2009. A protocol for classifying ecologically relevant marine zones, a statistical approach. Estuarine, Coastal and Shelf Science 83: 175–185.

Walker, D.I., Carruthers, T.J.B., Marrison, P.F., McComb, A.J., 1996. Experimental manipulation of canopy density in a temperate seagrass meadow: effects on sediments. In: Kuo, J., Phillips, R.C., Walker, D.I., Kirkman, H. (Eds.), Seagrass Biology. University of Western Australia, Perth, pp. 117–122.

Wedding, L.M., Friedlander, A.M., McGranaghan, M., Yost, R.S., Monaco, M.E., 2008. Using bathymetric lidar to define nearshore benthic habitat complexity: Implications for management of reef fish assemblages in Hawaii. Remote Sensing of Environment 112: 419-4165.

Williams, A., Bax, N.J. 2001. Delineating fish-habitat associations for spatially based management: an example from the south-easter.n Australian shelf. Marine and Freshwater Research 52: 513-536.