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Quarternary Coastal Evolution Adjacent to the Ningaloo Reef, Western Australia, and Implications for Land use Planning.

Bachelor of Science (Applied Geology) (Honours) 2002.

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Quarternary Coastal Evolution Adjacent to the Ningaloo Reef, Western Australia, and Implications for Land use Planning.

by

Nathan Blackwell

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A dissertation submitted in partial fulfilment of the Bachelor of Science (Applied Geology) (Honours).

School of Applied Geology

Abstract

The Ningaloo Reef is a fringing reef, which dominates part of the Gascoyne coast in the North West of Australia. It forms 280 km of segmented, narrow reef crests and lagoons. Reef morphology has dictated terrestrial and lagoonal sedimentation during the Quaternary. The reef supports a wide variety of important habitats and is of worldwide conservation and biodiversity significance. The value of the area has been recognised by establishment of the Ningaloo Marine Park and Cape Range National Park. The coastal plain adjacent to the reef is situated within the Carnarvon Basin and the regional geology is dominated by Late Tertiary to Late Cretaceous limestone anticlines, including raised reef terraces, which are expressed as the Cape and Giralia Ranges.

The dominant physical processes responsible for Quaternary coastal evolution and continued modification of the coastal system are: sealevel variations, oceanography and present and past climate. The Leeuwin and Ningaloo currents are the dominant regional currents in this area. The lagoonal current system consists of northerly long shore drift, wave-pumped influx over the reef crest, and lagoonal flushing through reef passes.

The Holocene evolution of the coastal plain adjacent to the Ningaloo Reef occurred in five stages; shelf erosion and shore face retreat, transgressive deposits, highstand deposits, regressive deposits and modern beach and foredune development. The first four stages are a direct response to Late Holocene sealevel variation, and the last is a consequence of the modern sedimentary system. A distinctive stratigraphy has developed as a reflection of these influences, with large parabolic dune fields deposited during transgression and highstand, relic coastal features (cliffed

shorelines, emergent marine embayments and relic-foredunes) generated during highstand and beach ridge plains formed during regression.

Limestone headlands, stranded marine embayments and an expansive Pleistocene desert dune plain dominate the regional geomorphology. The coastal plain in mapped areas is characterised by a limestone hinterland with a thin colluvial cover, adjacent to a narrow coastal strip of Holocene dunes, including sequences of linear dunes plains and relic-foredunes, large parabolic dune fields, and both rocky/cliffed and sandy shorelines. Significant degradation of this fragile environment occurs despite some land and tourist management strategies put in place. Degradation is associated with nodes of activity, where access track development has the greatest impact due to uncontrolled networks of tracks.

Geomorphological mapping of the coastal zone provided a regional data base, which was analysed in terms of natural, and anthropogenic coastal environmental impacts, plus the development of a land classification scheme based on substrate capability. Land system units (geological units, further defined by environmental characteristics) with low substrate capability are unconsolidated, commonly mobile units, with little to no vegetation cover over steep slopes and undulating topography, making them prone to sediment remobilisation. Land system units with a medium to high substrate capability consist of consolidated limestone with a thin to non-existent cover of colluvial, material and significant vegetation cover. The delineation of risk zones, based on GIS analysis identified areas of land particularly at risk of degradation due to a combination of substrate characteristics and level of land use. This study is useful for land management purposes as it quantifies the impacts on the coastal zone and allows for the development of more effective management strategies. A major review of land management practices in the region is currently being undertaken by government agencies, and the environmental data produced in this study will be of direct assistance.

Acknowledgements

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1 INTRODUCTION

The Ningaloo Reef forms a segmented barrier adjacent to 280 km of coast in the north west of Australia, making it the longest fringing barrier reef in Australia. The reef system supports a wide variety of important habitats many of which are of worldwide significance. The value of this area has been recognised by the development of the Ningaloo Marine Park. The Cape Range, Giralia Range and Pleistocene desert dunes and narrow Holocene fringe form the hinterland adjacent to the reef.

The coastal system associated with the Ningaloo Reef provides a valuable basis for the study of Quaternary coastal evolution. Evolution of reef as a coastal barrier and Quaternary sea level variations have resulted the evolution of a unique and fragile coastline. This study is intended to provide baseline information for environmental impact studies and land management of this coast.

Despite the relative isolation of this stretch of coast, degradation due to uncontrolled camping and access track development has been recognised as a particular problem adjacent to the Ningaloo Reef. This study aims to describe and map coastal geology, and to document the nature coastal degradation associated with the different land units. The term substrate capability was developed for the purposes of this study to enhance land unit descriptions by emphasising the dependence of the land unit's capacity to withstand natural and anthropological impacts on substrate characteristics, thus creating a land classification scheme useful for land management purposes.

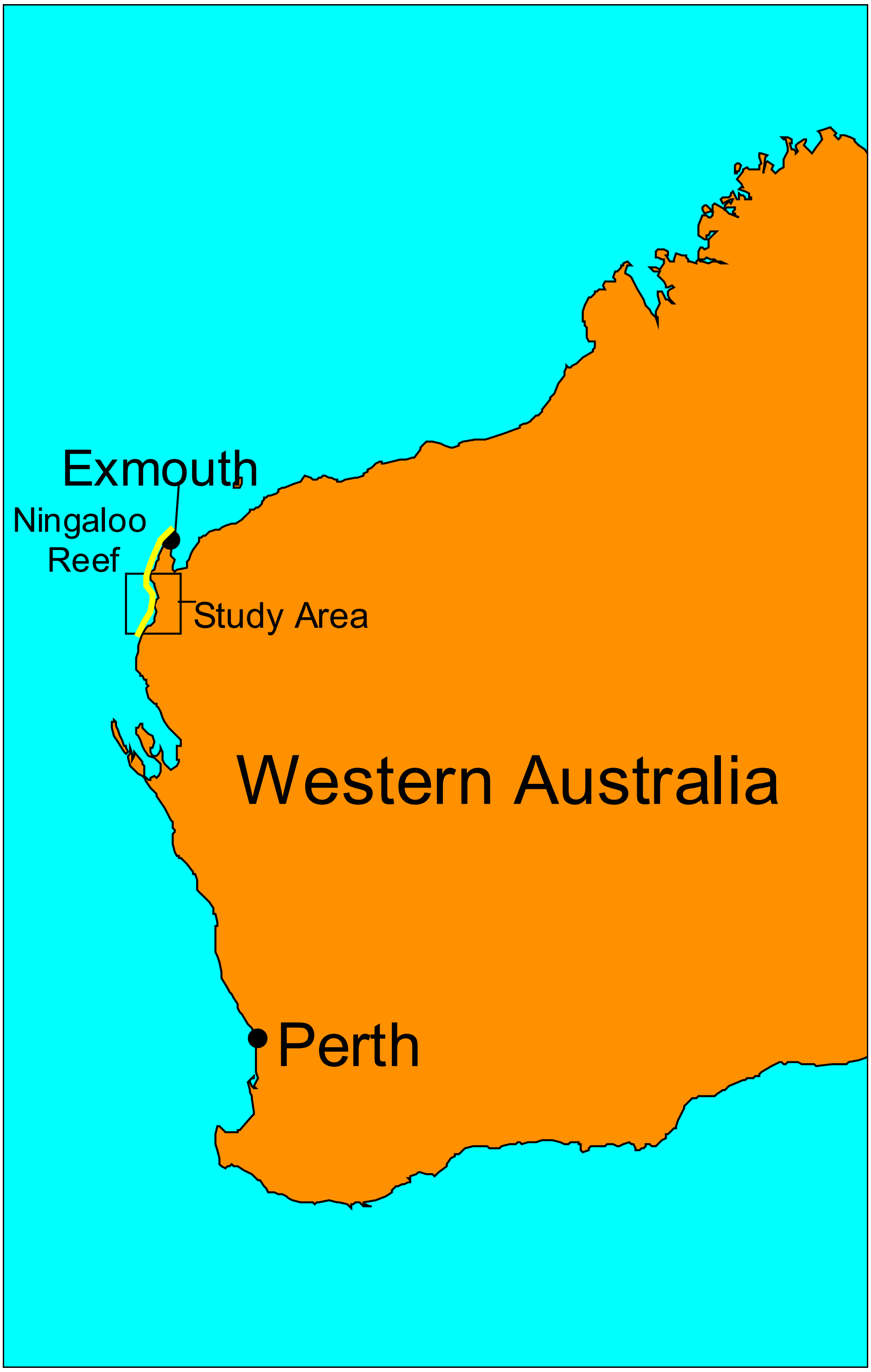


Figure 1-1. Location of the Ningaloo Reef and study area, Western Australia.

1.1 Aims and scope

This study aims to describe the coastal zone, and to document the nature and extent of coastal degradation in four mapped areas adjacent to the Ningaloo Reef. Specific aims include:

- To geologically map part of the hinterland adjacent to the Ningaloo Reef, with emphasis on areas of more intense land use.
- To describe the Late Tertiary – Quaternary coastal evolution of the study area with focus on the Holocene.
- To create Geographic Information System (GIS) data of geology, substrate capability, coastal access, nodes of activity and management zones.
- To establish a system of substrate capability to be incorporated into management practises in the region.

The areas of land studied are predominantly under the tenure of three pastoral. The Ningaloo Marine Park extends to 40 m above the high water mark, and the adjacent land is managed by Ningaloo Station (in the north, encompassing area A), Cardabia Station (the zone central, encompassing Area B and C) and Warroora Station (to the south, encompassing area D). Area C incorporates the Coral Bay Town site; see Figure 1-2 for the location of the four mapped areas.

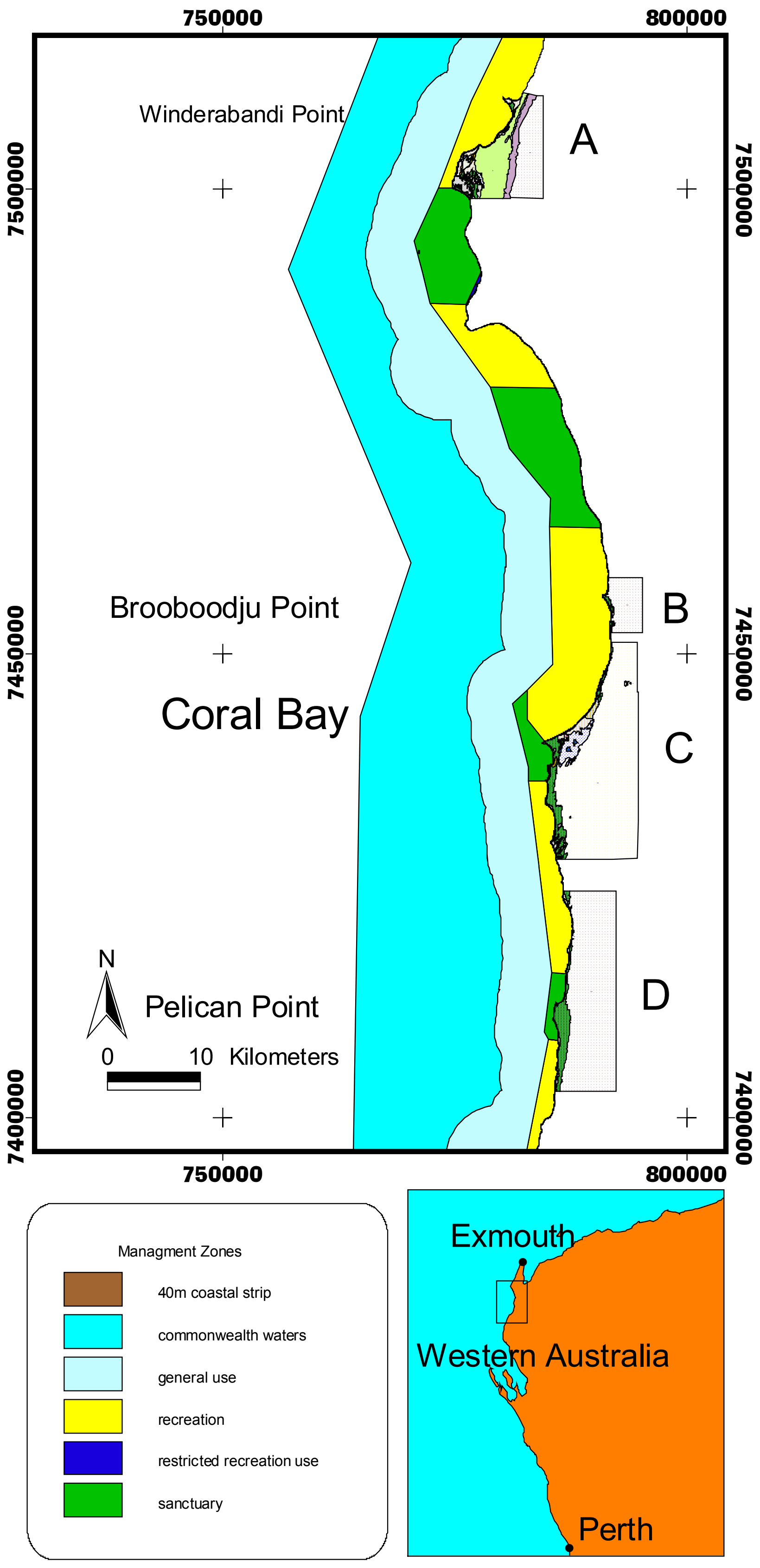


Figure 1-2 Location of mapped areas A, B, C, and D adjacent to the Ningaloo Reef.

1.2 Research Methodology

1.2.1 Reconnaissance

An initial study of all available air photos was used to select four coastal, high land use areas. The study was based on the southern half of the Ningaloo Coast as this area has been studied less than the north and is not contained within the Cape Range National Park. The abundance of access tracks was used to gauge the level of land use from Winderabandi Point in the north to just south of Pelican Point. The four areas chosen as suitable study regions were: Winderabandi Point, Bruboodjoo Point, Coral Bay and Pelican Point (see Figure 1-2).

The following photos where utilised, in digital format, for detailed air photo interpretation:

Area A-Winderabandi Point - Film WA4490(C) (Run1_5077, Run2_5108) 18/08/00

Area B-Brooboodju Point- Film WA4490(C) (Run13_5088) 18/08/00

Area C- Coral Bay- Film WA4310(C) (Run4_5149-5143, Run 5_5042-5046) 23/07/99

Area D- Pelican Point- Film WA4310(C) (Run 5_5054-5064, Run7_5122-5123) 23/07/99

For the purpose of interpretation and fieldwork, enlargements at 1:12500 were produced (including stereo pairs) and printed in colour on A3 sheets.

Aerial photo interpretation was used to determine preliminary geological boundaries, geomorphic units and access tracks. Landsat and ASTER imagery were used to help determine regional characteristics.

1.2.2 Fieldwork

During two weeks of fieldwork four high use areas previously selected were focused on and geology and geomorphology were ground truthed. Stratigraphy was documented by trench and shallow hole descriptions. Substrate and unconsolidated material were sampled for descriptive purposes. Land use, access and environmental degradation were verified and documented. Numerous ground traverses were also finished. Descriptions of lithology, sediment/rock type, slope stability and vegetation cover were completed. A large amount of GPS location data was collected for photo rectification purposes.

1.2.3 Classification and Terminology

The development of nomenclature and descriptions for mappable units was completed with the end use and probable users in mind. These users include marine park managers and land holders such as Station operators who will utilise the data for management and research purposes. Standard geological rock and sediment descriptions and mapping techniques were used to describe mappable units. However in order to add value to geological and geomorphological descriptions and to improve their relevance and application to land management, further environmental characteristics where attributed to each unit. The mappable units were therefore mapped and classified by a range of significant land characteristics.

A number of classification schemes have been utilised for environmental impact assessment purposes, incorporating holistic description of land areas encompassing multiple land characteristics such as geomorphology, vegetation and soil type. Gonzalez (1995) cite "land units" and "environmental units" as suitable terms for systems which place a heavy emphasis on vegetation variations and are associated with an urban environment. However, in this study of a relatively natural environment where land units are largely defined by geological/geomorphological characteristics, the term “land system units” is used. The term emphasises the interconnected environmental system affecting the Ningaloo Reef region. Land system units are delineated by geological boundaries, and then further defined by the unit’s substrate capability (see 1.2.4) and land use characteristics. Land system units are therefore interchangeable with geological units, but include important land management information. Section 5 contains the land system unit descriptions.

1.2.4 Substrate Capability Classification

Substrate Capability is a term developed for the purposes of this study to enhance land unit descriptions by emphasising the dependence of the land system unit’s capacity to withstand natural and anthropogenic impacts on substrate characteristics, thus creating a land classification scheme useful for land management purposes. Substrate capability can be defined as

“The capacity of a land unit’s substrate to withstand environmental impacts from natural processes and/or land use activities”.

A simple scale of 1-5, as outlined in 1.2.4, was used to assign a substrate capability index (SCI). The index is dependent on, and was developed by, a qualitative assessment of land unit characteristics. These include; unit thickness, stratigraphy, vegetation cover, topography, slope stability, constituents and consolidation.

Environmental impacts include Tropical Cyclones (including extreme rainfall, associated run off and cyclonic winds), drought conditions and associated loss of vegetation, sealevel rise, extreme (100 yr) storm events, tsunami impacts, fire and associated loss of vegetation. Anthropogenic/human impacts in this region are predominantly caused by recreational camping activities, the most obvious and destructive impact being the proliferation of access tracks and cleared camping sites. Denudation and habitat destruction caused by firewood collection and inadequate rubbish/waste disposal also impact on the region. Other human impacts include activities associated with Station work such as stock damage, fire management, land access and other land management activities.

1.2.5 Geographic Information System (GIS) Data Management

GIS was utilised for three main processes; geological mapping, access mapping and spatial data analysis.

Arcview 3.2 software was used for the majority of GIS work as CALM Marine Branch uses this program. Initial geological and access mapping involved transferring boundaries concluded during the field and interpretation work, in the form of overlays on hard copy air photos, into shape files. This was achieved by recognising the same boundaries on a base layer of orthorectified air photos with a ground resolution of 1.4 m (supplied by the Department of Planning and Infrastructure). The scale of the view used during digitising varied from 1:2000 to 1:3000.

Table 1-1. Unit characteristics used for the development of a substrate capability index (SCI) for coastal units adjacent to the Ningaloo Reef.

SCI	**1**	**2**	**3**	**4**	**5**
	Very Low	**Low**	**Medium**	**High**	**Very High**
Example Characteristics					
Consolidation/Constituents	Completely unconsolidated calcareous sand.	Unconsolidated calcareous sand.	Semi consolidated calcareous sand.	Semi consolidated calcareous sand.	Completely consolidated. (Limestone)
Slope stability/Topography	Steep slopes on undulating topography.	Steep slopes on undulating topography.	Medium slopes, gentle undulating topography.	Low slopes and flat topography.	Low slopes and flat topography.
Unit Thickness (depth) to limestone base.	Thick unconsolidated units over limestone base.	Thick unconsolidated units over limestone base.	Medium thickness units over limestone base.	Medium thickness units over limestone base.	Composed of limestone.
Vegetation Cover	None	Sparse grassland and coastal scrub.	Medium cover of grassland and scrub including established trees.	High cover if scrub, grasslands and small trees.	High cover if scrub, grasslands and small trees.

Figure 1-3. Camping site located in a foredune on Winderabandi Point. Illustrating associated loss of foredune vegetation

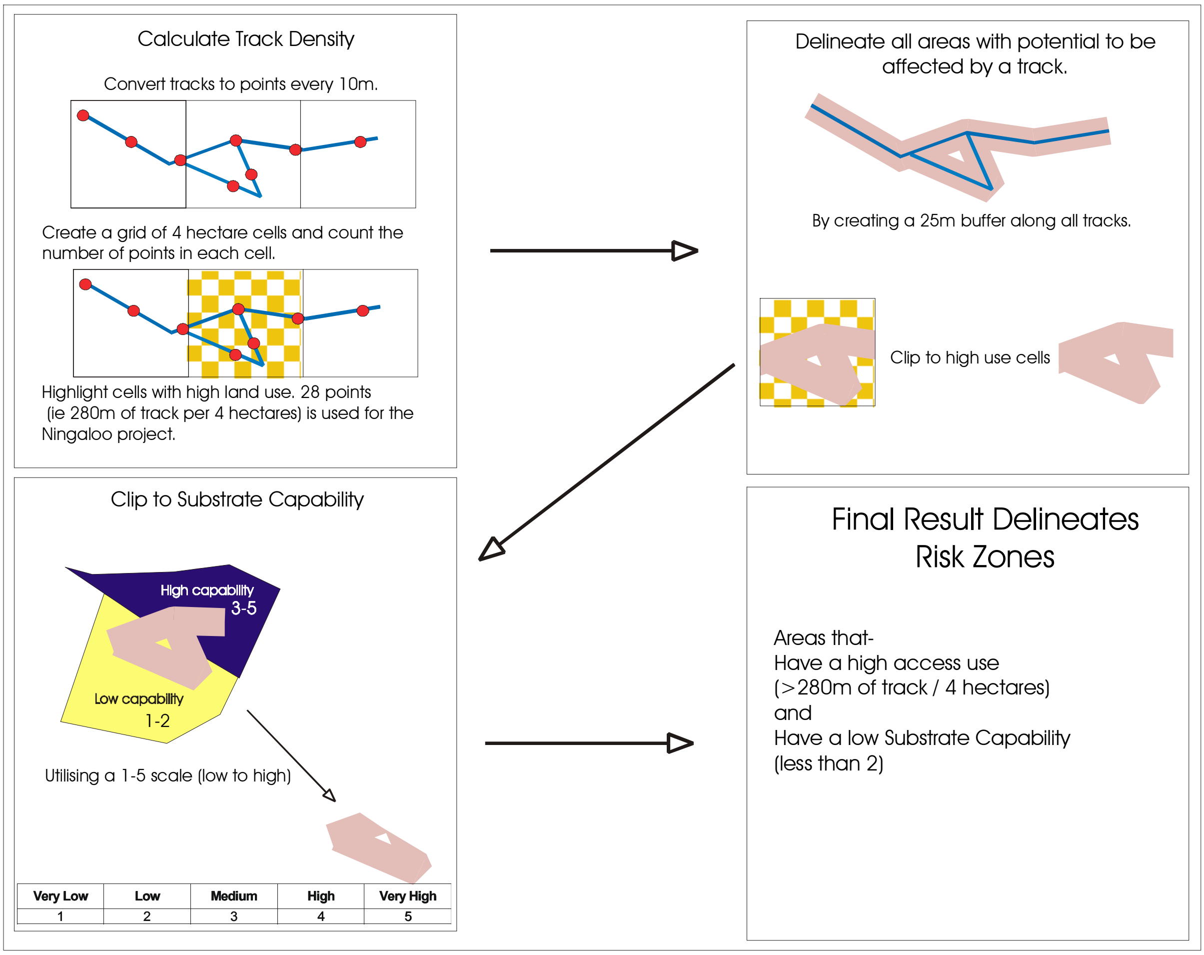


Figure 1-4. Flow diagram for the delineation of high-use and risk zones.

1.2.6 Data Analysis

Data analysis consisted of evaluation of the areal extent of high land use zones and high-risk zones within the mapped areas. Track density was used as a measure of land use. In order to measure the track density and then delineate high use zones the following method was employed (see Figure 1-4).

The access mapping previously created as line layers was converted to point data. This was achieved by automatically placing a point every 10m along the extent of all access lines. A grid covering each mapped area was then created with each cell having 200 m by 200 m dimensions (four hectares). The number of points in each cell was counted using an Arcview extension that automated the process. This allowed the classification of track density (land use) within the four-hectare cells.

A 25 m buffer was then created along the extent of the original access line theme. The reasoning for a cut off of 28 points and a 25 m buffer are described in Appendix 1. This buffered access theme was then cut by the spatial extent of the grid polygons (plus a 25 m buffer) with more than a 28-point count (i.e. 280 m of track in a four hectare cell). The final result was a number of polygons that delineate the high use zones.

These high use polygons were utilised to gain a quantitative assessment of the area of each land unit affected by current high land use activities by cutting geology layers to the spatial extent of high land use zones. Displaying the cut geology layers in terms of substrate capability then delineated high-risk zones. Areas of high use and a low substrate capability (SCI of 1 or 2, see 1.2.4) were deemed to be of risk zones.

1.2.7 Sample Preparation

Thin sections, including grain mounts, were prepared at Curtin University Applied Geology Department. Grain mounts were prepared by loosely packing sediment and bonding with epoxy resin and slides were ground to 30 μm.

2 REGIONAL GEOLOGY AND GEOMORPHOLOGY

The coastal plain adjacent to the Ningaloo Reef is situated within both the Exmouth and Gascoyne Sub-basins of the Carnarvon Basin, see Figure 2-1 (Hocking, 1990). The Exmouth Sub-basin is part of a southeastern set of troughs including the Barrow and Dampier Sub-basins that exist in the north of the Carnarvon Basin. The mainly Paleozoic Gascoyne Sub-basin is elongated north-south and is gently tilted to the west. The regional geology is dominated by a series of anticlines which find their surface expression in the Cape, Rough and Giralia Ranges (Wyrwoll et al., 1992). These ranges consist of dissected and deformed Mid-Late Tertiary and Late Cretaceous limestone overlain by Pleistocene eolian and marine sediments (van de Graff et al., 1980). The ranges are an indication that the coastal margins have experienced considerable tectonic activity during the Cenozoic. The coastal plain adjacent to the Ningaloo Reef flanks the Cape and Giralia Anticlines.

The Cape Range is expressed as a prominent northerly trending peninsula about 80 km long and 20 km wide. The maximum elevation is 314 m at Mt Hollister (Allen, 1993). The predominantly carbonate range is deeply dissected, with associated alluvial fans occurring on the coastal plain. A 500 m thick sequence of Palaeocene-Miocene rocks, the Cape Range Group, form the core of the range. Up to 10, 000 m of Phanerozoic rocks underlie this (Hocking, 1990). The west side of Cape Range is characterised by a series of emergent terraces, and the youngest of these is the

Tantabiddi Terrace which has been dated at 125 ka BP (van de Graaff, 1976). The interaction of sealevel change and range uplift has resulted in the development of this sequence (Wyrwoll et al., 1992).

The Ningaloo Reef forms a narrow reef crest and lagoons along the cape and dominates the western coast. The reef dictates wind, wave and tidal currents within the lagoon that

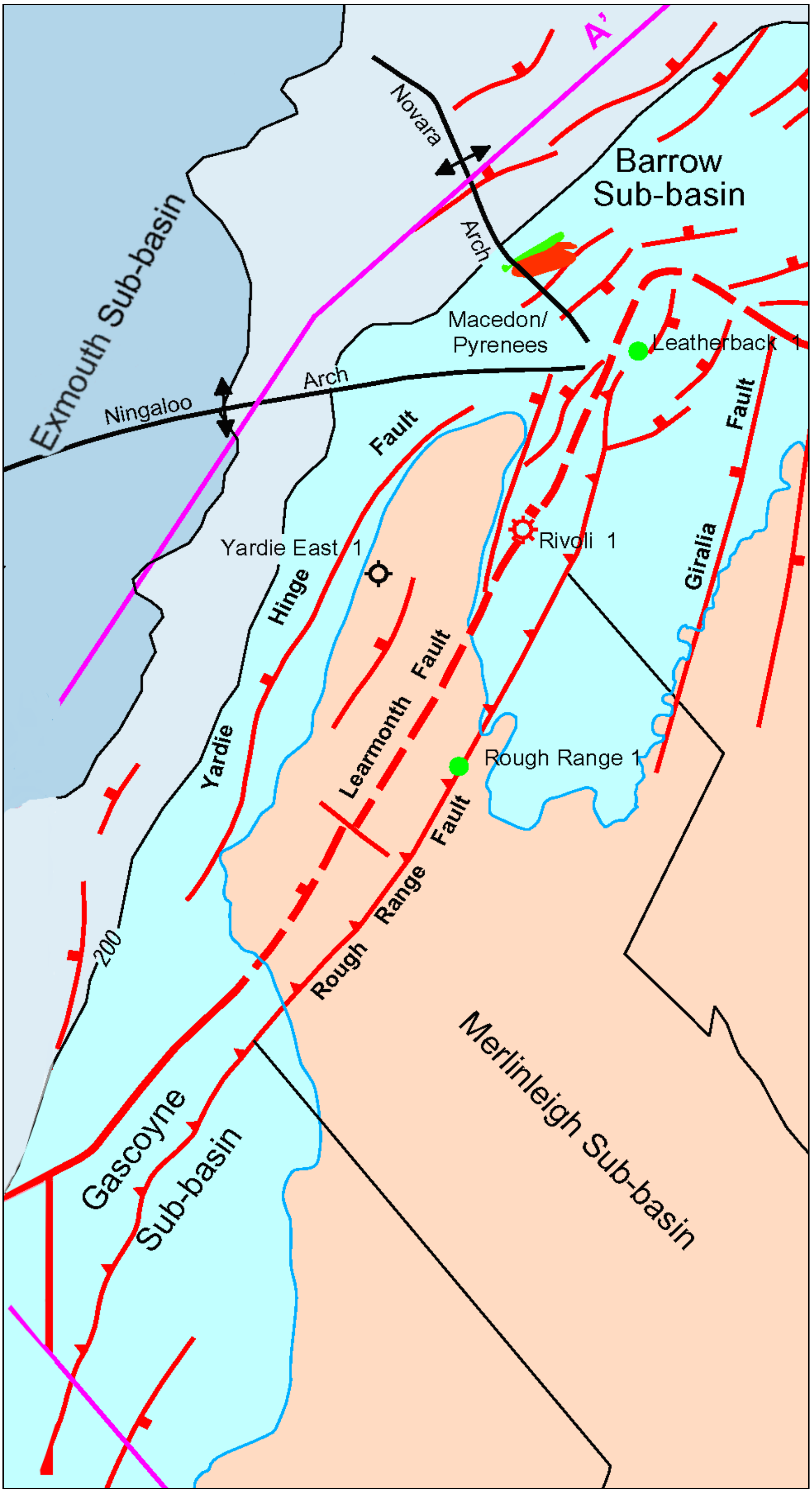


Figure 2-1. Basins and major tectonic features of the Northern Carnarvon Basin (Baillie et al., 1995).

in turn control both marine and terrestrial sedimentary systems. The reef also provides a modern analogue for the adjacent uplifted and preserved paleo-reefs (Sanderson, 2000).

The study area is contained in the physiographic region recognised by Hocking et al. (1987) as the Macleod Region. This region encompasses the Exmouth Peninsula south to the Gascoyne River (Figure 2-2) and is described as ".. a series of variably dissected anticlinal domes (Tertiary) separated by low-lying areas in filled by Pleistocene marine and eolian sediments" (Hocking et al., 1987).

Van de Graaff, (1980) described ten major physiographic units of the Yanrey Ningaloo 1:250 000 map sheet, and distinguished three main physiographic regions; a western region dominated by structural control with anticlinal highs and synclinal lows, a central region with very subdued relief and a duricrusted eastern region characterised by Mesozoic mesas and Proterozoic strike ridges (van de Graff et al., 1980). These regions were later named the Macleod Region, Marrilla Region, and the Ashburton Plain respectively (Hocking, 1985). Similar classification was applied by Hocking (1985) for the Winning Pool- Minilya 1:250 000 map sheet. Explanatory Notes for the Winning Pool and the Yanrey map sheets describe the immediate coast as sand dunes or calcareous coastal dunes with calcareous duricrust to the south. Coastal terraces and shoreline scarps are described by van de Graaff on the western coast of Cape Range and are further described as the geomorphological signature of the region (van de Graaff, 1976; Wyrwoll et al., 1992).

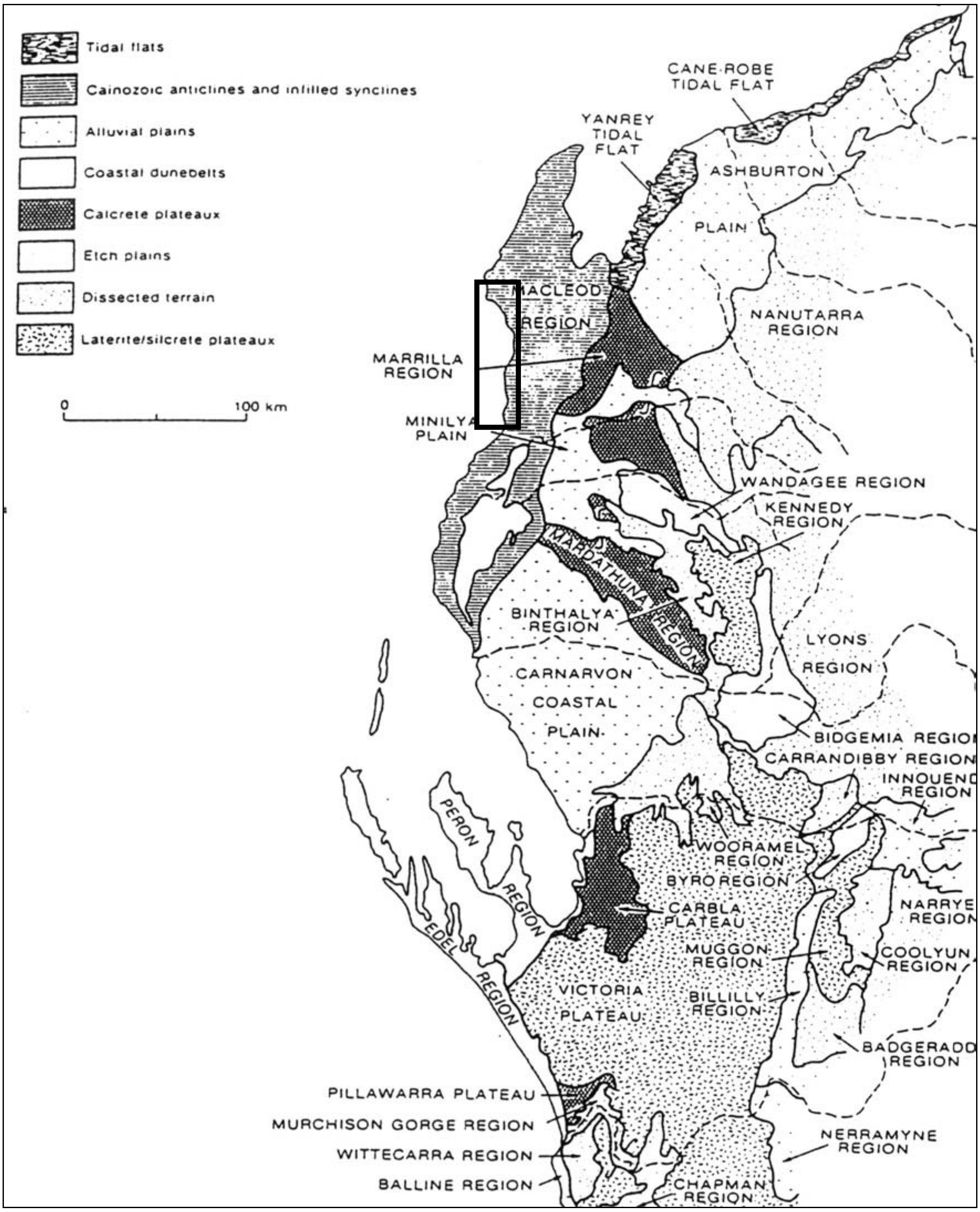


Figure 2-2. The physiographic regions of the onshore Carnarvon Basin (Hocking et al. 1987). The black box delineates the study region.

3 PHYSICAL PROCESSES

The coastal system adjacent to the Ningaloo Reef has have evolved by, and continues to be modified by, the actions of physical process operating in this area. Climate (both present and paleo-climate, oceanography and sealevel variations are the dominate physical process responsible for the evoluton and modification of this coast.

3.1 Climate

3.1.1 Present Climate

The climate of the Gascoyne Coast (the coast from the east side of Exmouth Gulf to Carnarvon) ranges from hot arid at the north of the Cape Range to warm semi-arid in the south, near Carnarvon. The annual average maximum temperature is 27 ^{o}C.

The region receives both winter (frontal) and summer (cyclonic) rain averaging 300 mm per year (see Figure 3-2) (WA Ministry for Planning, 1996). This rainfall is highly variable and may differ by up to 40% around the usual 200-300 mm per year range. This high variability is due to the impact of extreme weather events, notably Tropical Cyclones and major storms.

The predominant wind direction for the Gascoyne Coast in from the south. Figure 3-1 illustrates that these southerlies exist all year round, only changing to northerlies during Tropical Cyclones and storms. Wind speeds recorded at Tantabiddi well, on the west side of the Cape Range, range from 1-3 m/s (≈2-6 knots) to over 10 m/s (>19 knots) (CALM, 1998). The persistent southerly wind drives both modern eolian deposition and contributes to northerly lagoonal currents.

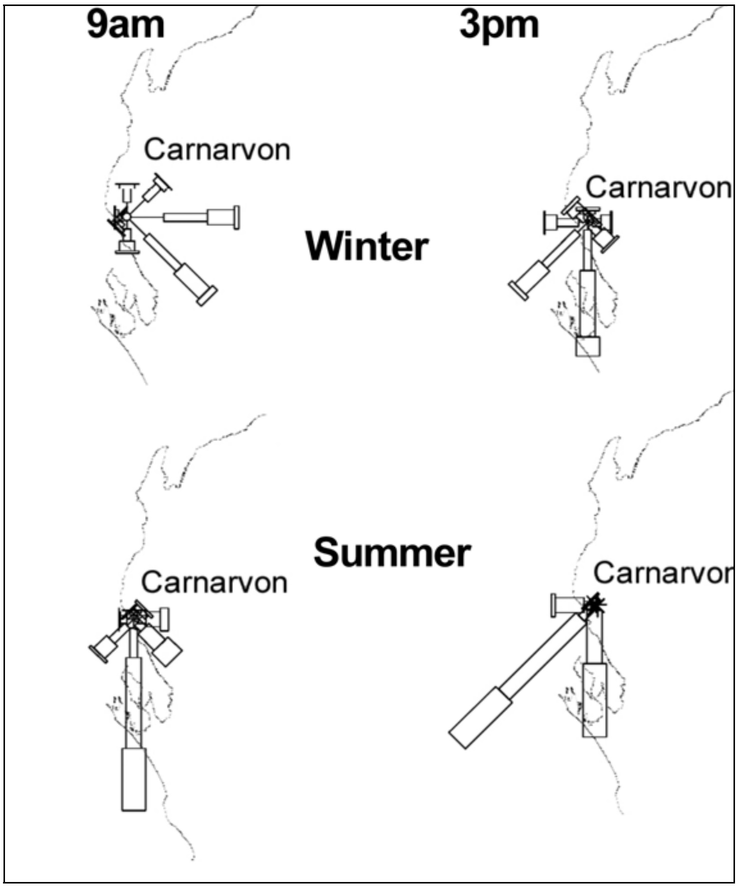


Figure 3-1. Carnarvon wind roses for summer and winter at 9 am and 3 pm. (adapted from Bureau of Meteorology (1999).

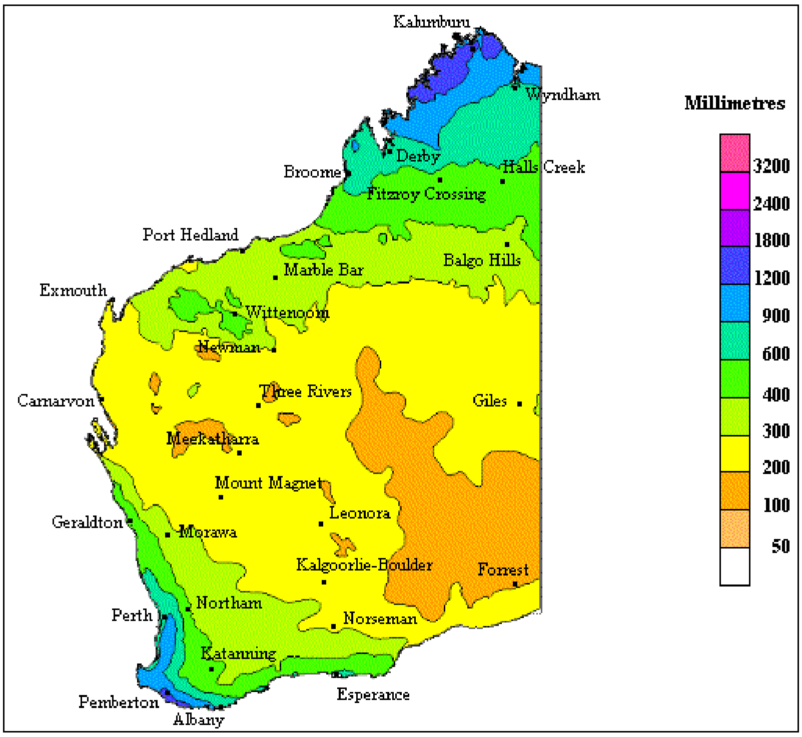


Figure 3-2. Average WA rainfall based on standard 30-year climatology from 1961 to 1990. (Adapted from Bureau of Meteorology (Bureau of 1990).

3.1.2 Tropical Cyclones

Tropical cyclones are an important characteristic of the climate in North West Australia. These extreme events are prevalent in the Cape Range region that expects to experience a severe Tropical Cyclone once every 3-4 years (Bureau of Meteorology, 1998). The strong winds associated Tropical Cyclones are predominantly from the north and can include wind gusts over 280 km/hr. The anticlockwise rotation of a Tropical Cyclone produces the northerly wind direction when approaching the North West Coast. Table 3-1 outlines the frequency of cyclone impacts on Learmonth, on the east of Cape Range, and the expected damage from the various categories.

Table 3-1. Cyclone intensity and frequency at Learmonth adapted from Bureau of Meteorology data

Category	**Maximum Wind Gust.(km/hr)**	**Typical Effects**	**Number of Times Recorded at Learmonth (1910-2000)**
1	Less than 125	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings.	22
2	125-170	Minor house damage. Significant damage to signs trees and caravans. Heavy damage to some crops. Craft may break moorings. Risk of power failure.	10
3	170-225	Some roof and structural damage. Some caravans destroyed. Power failure likely.	2
4	225-280	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failure.	0
5	More than 280	Extremely dangerous with widespread destruction.	1

The reduction in air pressure and wind stress on the sea surface associated with a Tropical Cyclone can cause a storm surge. A storm surge is a raised dome of seawater typically 60 to 80 km wide and two to five meters above sealevel. The reduced pressure causes the sea to rise by about 10 cm per one hectopascal reduction in air pressure (Australian Institute of Marine Science, 2002).

Tropical Cyclone Vance passed close to the Cape Range on the 21st of March 1999. A record wind speed for the Australian mainland of 267 km/hr was recorded at Learmonth 35 km south of Exmouth. The combination of a high tide and Tropical Cyclone associated 5 m storm surge caused severe erosion at the beachfront and marina at Exmouth and along the west coast and stranded three large barges in Onslow (Bureau of Meteorology, 2002). Where Tropical Cyclone Vance crossed the coast 200-300 mm of rain was recorded (the annual total) and the associated runoff and flooding caused a large proportion of the property damage in Exmouth.

Evidence of northward facing shores having relatively high foredunes is an example of the influence of Tropical Cyclones on the Ningaloo coast (see 5.2.4). Other examples include significant erosion and reworking of the immediate coastline, as shown in Figure 3-3. At this location just south of Pelican Point, access tracks have been removed as the shoreline was cut back.

Figure 3-3. Significant erosion and reworking of the immediate coast just south of Pelican Point (area D) caused by a Tropical Cyclone. Photo taken June 2002.

3.1.3 Extreme Storm Events

During fieldwork for this project, June 2002, the North West Cape was hit by a large storm event. The storm was significant due to the 304.6 millimetres of rainfall recorded in Exmouth in the 24 hours to 9 am on June the 5th, the wettest June day on record in Western Australia. Rather than cyclone activity, the intense rainfall was caused by a strong northeast to northwest convergence area that developed over the North West Cape beneath a northwest cloud band. This produced a band of slow-moving showers and thunderstorms, and sustained, heavy rainfall (Bureau of Meteorology, 2002). Significant damage was caused in Exmouth including the flooding of the power station, the main road being washed out and two trawlers capsizing in the marina due to run off influx (see Figure 3-4).

Figure 3-4. Two trawlers capsized in Exmouth boat harbour by the flow into the marina from a major creek during the June 2002 storm.

3.2 Paleoclimate

The Plio-Pleistocene paleoclimate of the north west of Australia was characterised by more arid conditions and an Interglacial-glacial climate regime.

Palynological work by Sander (Sander van der Kaars etal., 2002) on a deep-sea core, taken 60 km west of the Cape Range, investigated the Quaternary ecology and climate of the Cape Range Region. The paleoclimatic conclusions are based on floral assemblages derived from the pollen record. These records suggest drier conditions and a reduction in summer (cyclonic) rain in the last 46 ka compared to 100-64 ka BP. The record also shows periods of maximum summer rain at 100, 80 and 70 ka BP (Sander et al., 2002).

A review of paleoclimate events in the Cape Range Region concluded that the closing stages of the Tertiary were characterised by a wetter climate than present

(Wyrwoll, 1993). By the middle Pleistocene, a more arid, Interglacial-glacial, climate regime had developed in the Cape Range. The exact timing of the onset of aridity in not known.

The late Pleistocene (500 ka BP) climate was characterised by a series of glacial and Interglacial stages. These stages consist of long (100 ka) glacial periods during which the climates were drier than the Holocene and short (10 ka) Interglacials during which time the climate was similar to or wetter than that of today (Wyrwoll, 1993).

Sr/Ca ratio work on Last Interglacial reefs from Vlaming Head and the modern reef have been utilised to resolve paleo sea surface temperatures (McCulloch et al., 2000). The record supports the hypothesis that Last Interglacial climate was similar to today. Coral within the reef studied was dated by Stirling (1998) at 128-122 ka BP (Last Interglacial). The *Porites* coral gave a reproducible summer maximum ranging from 23 ^{o}C to 28 ^{o}C and winter minima ranging from 23 ^{o}C to 20 ^{o}C and an annual mean temperature of 24 ^{o}C (McCulloch et al., 2000). This is similar but slightly cooler than the modern sea surface temperatures, for example, 1987-1993 had a summer maximum of up to 29 ^{o}C and winter minimums of 21 ^{o}C. However evidence of widespread Last Interglacial reef growth along the Western Australian coast as been cited as evidence for increased sea surface temperatures caused by a significantly stronger Leeuwin Current at that time (Collins et al., 1991).

Three controls have been suggested as causes of increased aridity during Glacial Maximum periods. A reduction in sealevel during the Last Glacial Maximum (c. 18 ka BP) would have exposed much of the shallow shelf in northern Australia. An enhanced Indian Ocean trough, marked ridging over eastern Australia and another trough further east would have reduced sea temperatures, reducing rainfall (Webster et al., 1978). A reduction in tropical cyclone frequency during glacial maximum periods has also been postulated by Hobgood and Cerveny (1988). As 40% of the current mean annual precipitation of the Cape Range is cyclone induced, this is a significant factor in increased aridity.

The greatest impact of Plio-Pleistocene paleocliamte was the development of the desert dune terrain that dominates much of the Gascoyne Region. These dunes are a response to arid periods and associated desertification.

3.3 Oceanography

3.3.1 Regional Current System

The Leeuwin Current dominates regional oceanography of the Ningaloo Reef region. The Leeuwin Current is a warm, relatively low salinity, southward flowing current located at the seaward margin of the continental shelf. This current frequently influences Ningaloo Reef and the Houtman Abrolhos reefs off Geraldton, 500 km south of the Ningaloo Reef, and continues to flow through into the Great Australian Bight. This current is strongest during the winter and autumn months, where sea surface temperatures can be up to 4 ^{o}C warmer than adjacent oceanic waters. The current is responsible for larval delivery to southern reefs, and it may also be responsible for suppressing upwelling (Pearce, 1994).

3.3.2 Local Current System

The current system within the Ningaloo lagoon can be attributed to a combination of tide, wind and wave action (Hearn et al., 1988). Hearn devised a model for current flow in the lagoon at Sandy Bay, north of Yardie Creek (see Figure 3-5 and Figure 3-6). This suggests a southerly flow during winter and autumn and a northerly flow during summer and spring on the seaward side of the reef, and a northerly flow nearshore. This is attributed to wind driven currents being dominant in the shallower lagoon and the Leeuwin and Ningaloo currents being dominant in the deeper seaward side. Wave pumping circulation completes the cycle through passes in the reef crest (Figure 3-5; (Hearn et al., 1988) . Figure 3-6 details the current system operating in a specific lagoon in the Pelican Point area (area D). Current analysis work by Sanderson (2000) on Winderabandi and Turquoise Bay showed that the currents were dominated by both semi-diurnal and high frequency fluctuations. Cellular circulation occurred in both lagoons with a net drift to the north. The strongest currents are tidal currents entering and exiting the reef with velocities up to 50 cm/s. Fluctuating water levels due to tide action and wave forcing (pumping) also contribute to circulation (Sanderson, 2000).

3.3.3 Tides

The Ningaloo Reef lies just to the north of the transition from the diurnal and micro-tidal zone in the south to semi-diurnal and macro-tidal zone in the north (Simpson et al., 1986). The reef track experiences mixed tides, dominated by semi-diurnal, with a maximum spring tidal range of 2m (D'Adamo et al., 2001).

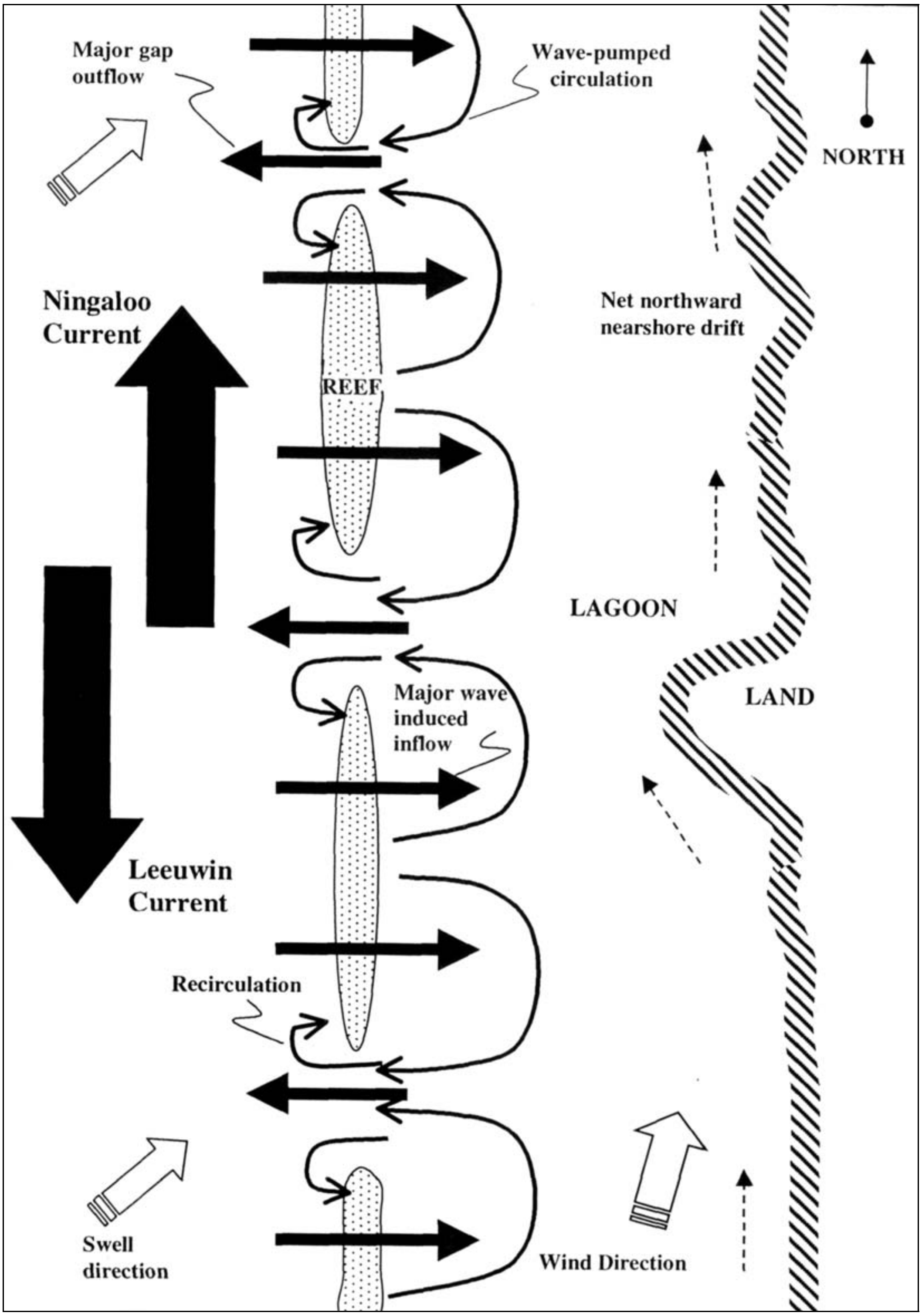


Figure 3-5. Schematic diagram of the main flow patterns believed to operate most consistently at Ningaloo Reef under the dominant forcing of wave-pumping, from (Hearn et al., 1988) and (D'Adamo et al., 2001)

The large black arrows indicate regional currents, hollow arrows indicate wind and swell direction, dashed arrows indicate nearshore drift direction and small black arrows indicate local current directions.

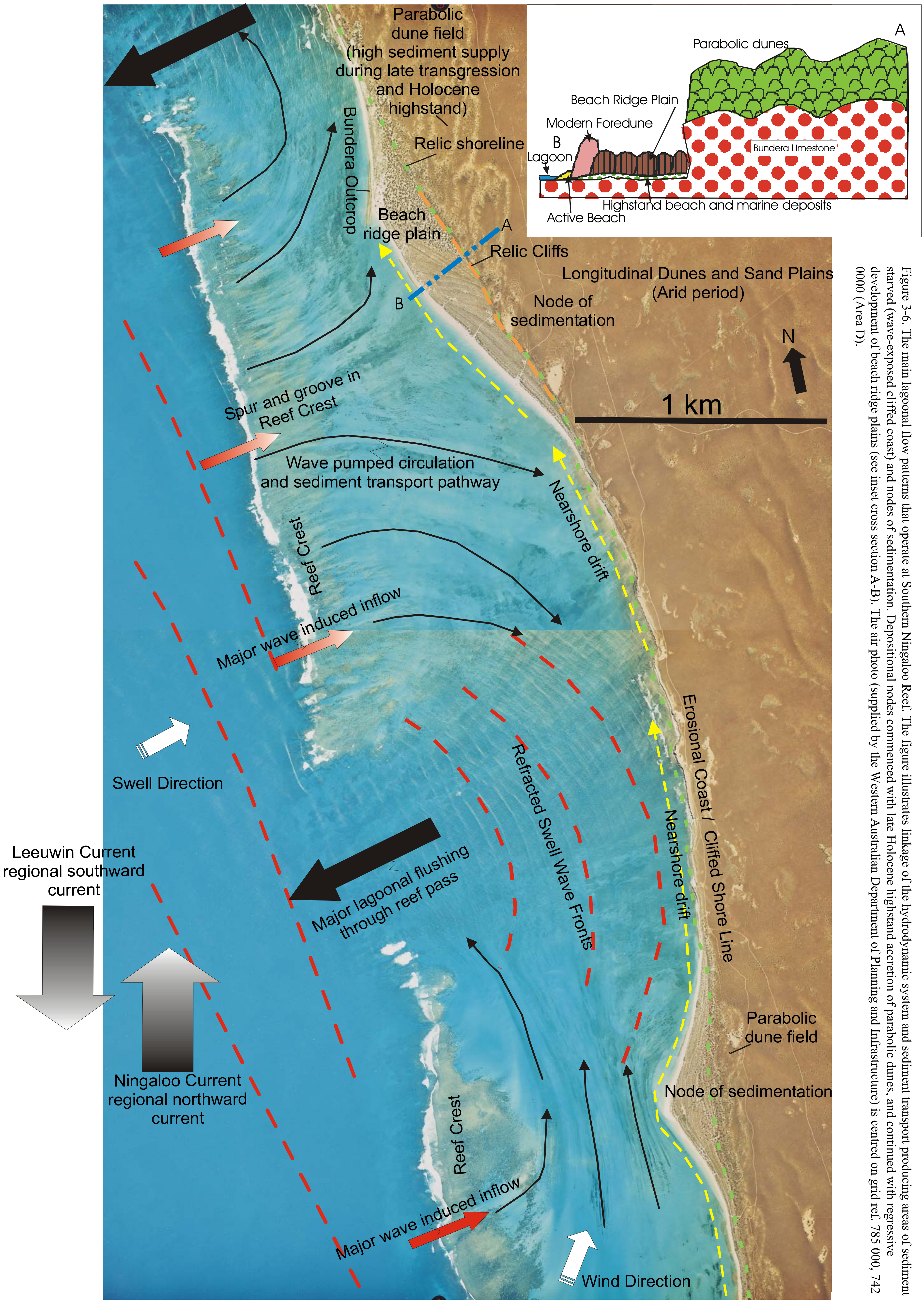
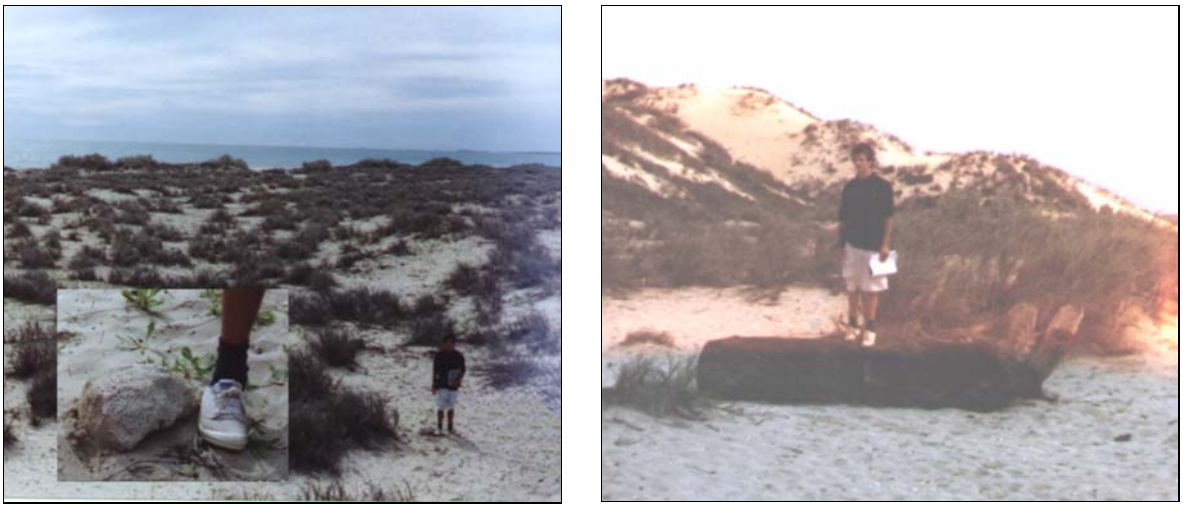


Figure 3-6. The main lagoonal flow patterns that operate at Southern Ningaloo Reef. The figure illustrates linkage of the hydrodynamic system and sediment transport producing areas of sediment starved (wave-exposed cliffed coast) and nodes of sedimentation. Depositional nodes commenced with late Holocene highstand accretion of parabolic dunes, and continued with regressive development of beach ridge plains (see inset cross section A-B). The air photo (supplied by the Western Australian Department of Planning and Infrastructure) is centred on grid ref. 785 000, 742 0000 (Area D).

3.3.4 Tsunamis

Tsunami waves are usually the result of earthquakes that displace a large amount of seawater by the rapid deformation of the earths crust. A tsunami wave is a fast moving pulse (>900 km/hr) with wavelengths greater than 100 km. The wave has a small height differential in deep ocean (<1m) but as it crosses a continental shelf into shallower water the wave "ramps up" and can reach 5-10 m high. The impact of the wave, that can reach 100s of meters inland, can be catastrophic. Three recorded tsunami events have occurred on the North West Coast in 1883, 1977 and 1994 (National Oceanic and Atmospheric Administration, 2002). The event in 1994 has been estimated at reaching 4m along the North West Cape. The wave resulted in mass fish standings and large coral heads washed in to the dunes. Evidence of swash from an extreme wave event was noted in the Coral Bay Area (area C). Figure 3-7 A is an example of large blocks of coral present up to 40 m from the beach. Figure 3-7 B is one of 4 logs found 10 m from the beach behind a low foredune. These objects could have been deposited by either a tsunami or a Tropical Cyclone but they illustrate the power of the extreme wind and wave events in this region.



A **B**

Figure 3-7. Possible tsunami wash over or Tropical Cyclone debri. A is a reef fragment located ≈40 m from the beach and B is on of 5 logs located 10 m from the beach on the landward side of the foredune. Point Maud, area C.

3.4 Sealevel Variations

The geomorphology and morphostratigraphy of the coastal plain adjacent to the Ningaloo Reef has been largely controlled by Quaternary sealevel events. Four distinct sea-level events have occurred during the Quaternary. These are the Last Interglacial transgressive phase and highstand at around 125 ka BP, the following glacial regressive phase with a glacial lowstand at around 20 ka BP, then a transgression and Late Holocene highstand at 5 ka, followed by regression to current sealevel.

3.4.1 Last Interglacial Transgression

The Tantabiddi Member of the Bundera Limestone represents the Last Interglacial highstand on the North West Cape. This Member is commonly exposed as notched terraces with Last Interglacial reef 2-3 m above mean low water spring tide. This level most likely represents a minimum sealevel as the coral heads were probably growing 0.5-1 m below mean low water spring tide. The minimum sealevel recorded in this unit is therefore 4 m higher than present sealevel (Murray et al., 1991; McCulloch et al., 2000). Stirling et al. (1998) dated the Tantabiddi Last Interglacial reef at 128 ka BP (U-Th series). This date for the peak of the Last Interglacial correlates with data from other Last Interglacial reefs such as Abrolhos reefs dated at 125±1.8 (Eisenhauer et al., 1996) and Barbados reefs dated at 129.1±0.8 (Gallup et al., 1994). This date indicates that a substantial period of stable sealevel high occurred between 115 and 130 ka BP allowing the significant growth of Last Interglacial reefs.

3.4.2 Last Glacial Regression

A regressive phase ensued after the highstand at 125 ka BP until 20 ka BP. This overall regression phase included up to 6 periods of transgression and concludes at

20 ka BP with sealevel 125m below present level. Shackleton (1987) derived a sealevel curve primarily from oxygen isotope stages corroborated by dated coral terraces in Papua New Guinea. These terraces have been preserved due to a considerable amount of uplift in the region. The only onshore record during the regressive phase in the Cape Range region are alluvial fan units such as the Mowbowra Conglomerate that developed as a response to both uplift of the Cape Range and sealevel fall (Wyrwoll et al., 1992).

3.4.3 Last Glacial Maximum and Postglacial Transgression

A period of transgression occurred from 20 ka BP from 125m below present levels until approximately 5 ka BP. Yokoyama et al. (2001) reviewed sealevel observations and models for the Last Glacial maximum around the Australian coast. A series of sealevel curves from the Last Glacial maximum to present are shown in Figure 3-9 for four locations around Australia. These curves were produced from using rigorous glacio-hydro-isostatic modelling. Dating of submerged shorelines at such as at the Great Barrier Reef (1.8 ka ^{14}C BP at 133m) corroborate these models (Yokoyama et al., 2001). No submerged shorelines have been studied in the Cape Range area.

3.4.4 Late Holocene Highstand and Regression

There is evidence of a Holocene highstand on the coastal plain adjacent to the Ningaloo Reef. Wyrwoll et al. (1992) cite clear field evidence for a highstand of possibly 1-2m but are not specific. It is assumed that the authors are referring to the numerous salt flats along the coast. Salt flats are present in all mapped areas but area D (see 5.2 and maps 1-4 for location and descriptions). The salt flat to the east of Coral Bay Town Site is the most prominent example of a marine embayment stranded by the Late Holocene transgression (Kendrick, 1990) dated a cardiid bi-valve collected from a pale sandy coquina bed underlying this salt flat at 5230±60 years BP. This is considered to represent the approximate time of cessation of marine exchange to the embayment. A similar shell bed was found in the supra-tidal flat to the north of Bruboodjoo Point in area B. A reconstruction of mid to Late Holocene marine environments and sea levels obtained from of the remains of relict inter-tidal or subtidal indicators was reviewed by Baker (2001), who also describes Holocene sealevel fluctuations derived from various coastal sites including Rottnest Island, where serpulid tubeworms were dated at 5050±290 y BP at 2.1m above present sealevel.(Eisenhauer et al., 1996). Bedded rudstone pavements, 0.8m above mean sea level, from the Abrolhos Islands have been dated at 6323±23 y BP. This suggests a Holocene highstand of approximately 1.8m (Freeman, 2002).

The effect of these sealevel variations on the geomorphological development of the coast adjacent to the Ningaloo Reef are described in section 7.

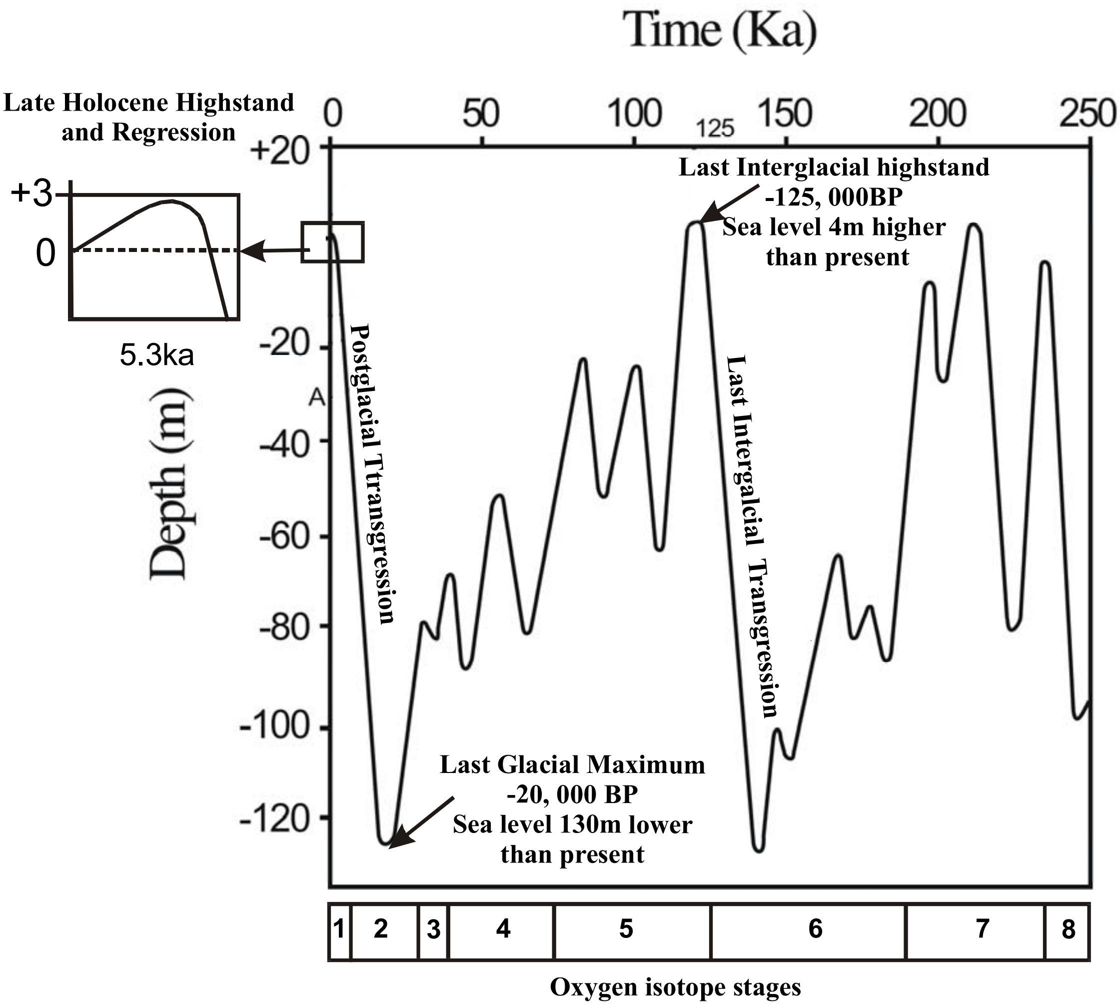


Figure 3-8. Sealevel fluctuations during the Late Quaternary.

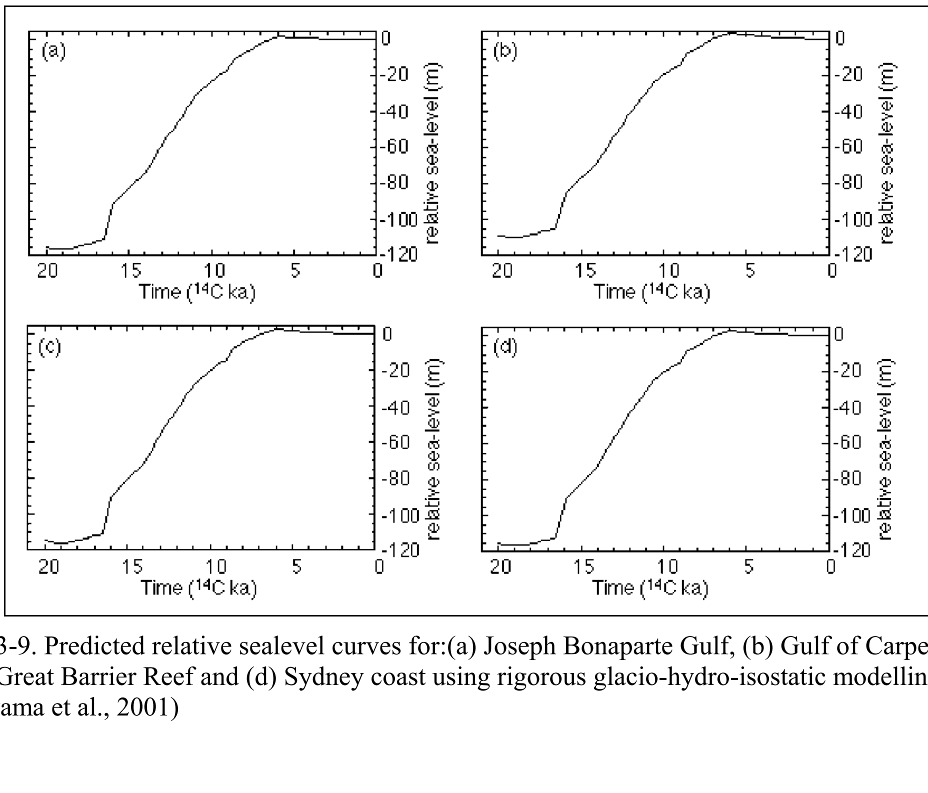


Figure 3-9. Predicted relative sealevel curves for:(a) Joseph Bonaparte Gulf, (b) Gulf of Carpentaria, (c) the Great Barrier Reef and (d) Sydney coast using rigorous glacio-hydro-isostatic modelling. (Yokoyama et al., 2001)

4 ANTHROPOGENIC IMPACTS ON THE NINGALOO COAST

This section is a summary of the anthropogenic impacts affecting the four mapped areas studied in this project, including a number of specific observations made during fieldwork.

The Ningaloo Coast and the Cape Range are currently experiencing an increase in tourism and subsequent impacts, and as this stretch of coast becomes more popular, it is put under increasing pressure from anthropogenic impacts. The major land use in the region is for recreational activities such as camping and fishing. The four mapped areas in this report were chosen as they are high land use zones in the southern end of Ningaloo Reef; the high land use is due to the popularity of these areas for camping and fishing. The level of anthropogenic impacts reflects this high land use. Other anthropogenic impacts are associated with pastoral leaseholder activities such stock grazing, fire management and land access.

The greatest impacts occur due to vehicular access. Access track development and use is frequently uncontrolled, causing the proliferation of networks of tracks. Significant degradation of this fragile environment is associated with nodes of activity that are typically established camping sites, often associated with boat launching points, heavily used access tracks or facilities such as rubbish dumps.

Warroora (area D) and Ningaloo Station (area A) have in place some land and tourist management strategies. The most evident aspect of this management is a caretaker in both stations. These caretakers act as guides and regulatory figures. Other activities include restriction of access to known problem areas or particularly fragile environments. Both stations charge a nominal fee for camping. Nevertheless there are significant anthropogenic impacts in the areas.

Two specific activities cause the majority of the degradation in the coastal zone adjacent to the Ningaloo Reef; access tracks and camping site development. The impacts of access tracks on the coastal plain are predominantly denudation of the immediate track. Major degradation occurs when the substrate is unable to withstand increased traffic. When this occurs denudation and erosion can start to effect large areas. Different substrates and land units in the mapped areas respond to vehicle impacts differently (see section 0).

A “semi structured” camping area with up to thirty separated sites has developed in the Winderabandi Point area (area A), Figure 4-1 A. This area, that can accommodate over 60 people, is located along a 400 m stretch of coast and within 100 m from the beach on a narrow beach ridge plain adjacent to the modern foredune. Apart from the localised denudation, the main impact here is waste disposal. This occurs because of the lack of toilet facilities and poor rubbish disposal. Each site chooses its own pit toilet facilities that are buried when the site is vacated. A rubbish tip has developed within 1 km of this node of activity but has recently been closed by Ningaloo Station (see Figure 4-1 B). The tip is still being used and mobile rubbish has polluted a large area to the north of the tip, however, due to the strong prevailing southerly wind. This camping site is the exception in the four mapped areas as the majority of camping sites are dispersed and relatively isolated. It is arguable that this situation, where campers and the majority of associated impacts are focused, rather than dispersed, is preferable.

The effect of access track development on limestone with a thin sandy veneer is shown in Figure 4-1. This example is located in area B just east of the supratidal flat (grid ref. 789 640, 7456 370). The track is situated on a narrow strip of limestone pavement that underlies the supratidal flat and outcrops at the boundary of the sand plain to the east.

Degradation developed in the modern foredune is shown in Figure 4-1 D. This is caused by this area becoming a major access point to the beach (grid ref. 776 240, 7504 480).

One of the major areas of degradation in area C is to the south of Coral Bay and illustrated in Figure 4-1 E. This area within 3 km of the Coral Bay Town Site (grid ref. 783 230, 7436 130) experiences considerable vehicle traffic due to the proximity to Coral Bay and the popularity of this area for wind surfing. The access tracks are under considerable pressure not only from four wheel drive vehicles but also people attempting the trip in two wheel drive vehicles, which frequently get bogged, causing considerably more damage to the dune units.

The degradation caused by a camping site and access node in area D is shown in Figure 4-1 F (grid ref. 784 000, 7402 890). The node of activity is situated on the boundary of a beach ridge plain and the modern foredune.

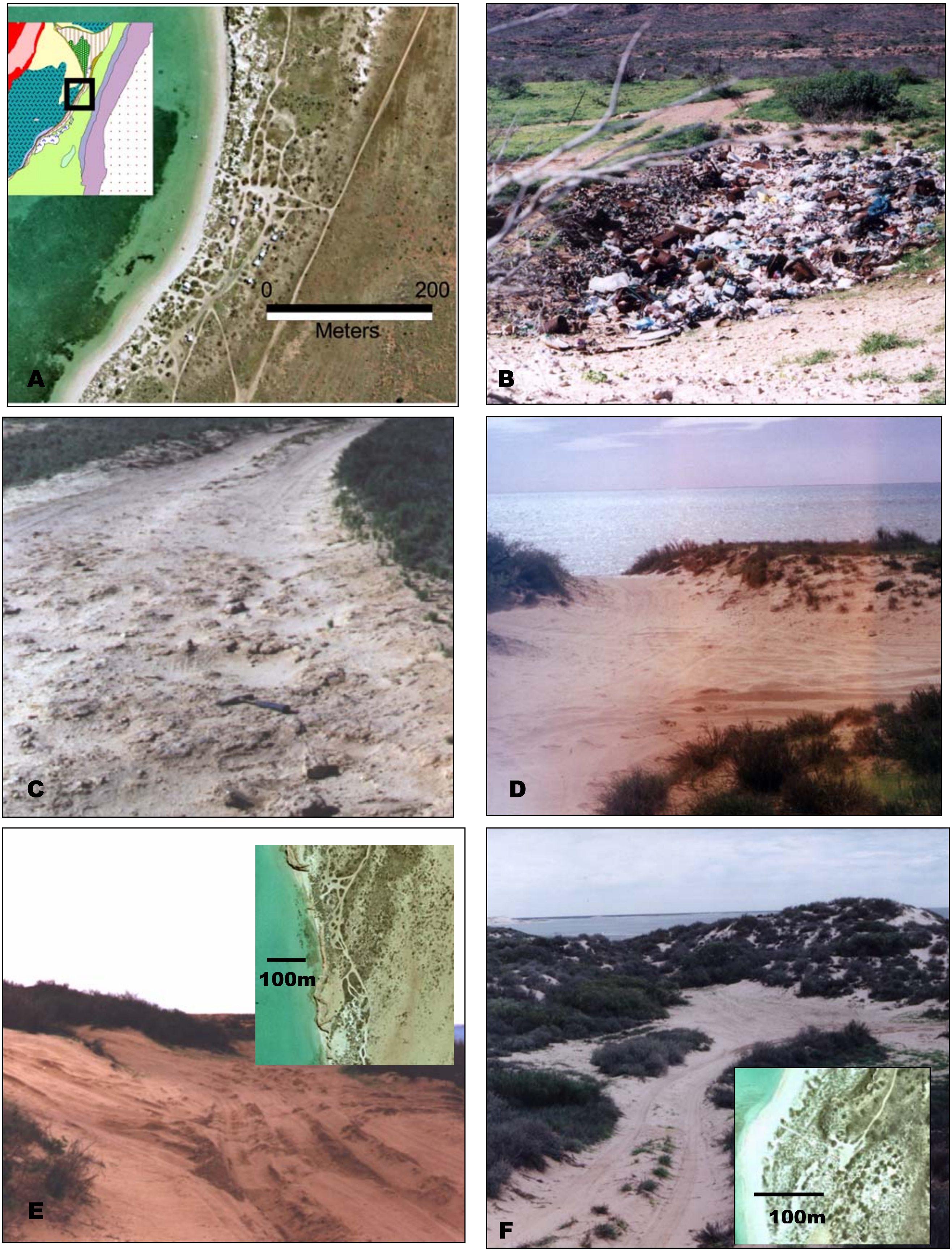


Figure 4-1. Examples of anthropogenic impacts on the coastal plain adjacent to the Ningaloo Reef.

A. Aerial photograph of the major node of activity in area A. **B**. Rubbish tip in area A. **C.** Access track development on limestone with a thin sandy veneer. **D.** Degradation developed in the modern foredune. **E.** A major area of degradation in area C.**F.** Camping site and access node in area D.

5 COASTAL GEOMORPHOLOGY

The geomorphology of the coastal zone adjacent to the Ningaloo Reef reflects the presence of the reef and Quaternary sealevel variations in landform development. The coast adjacent to the reef has been described as dune and cuspate spit coast (D A Lord & Associates Pty Ltd, 2000) . This coast is characterised by the presence of the barrier reef offshore and cuspate forelands and beach ridges formed due to wave refraction and sealevel regression onshore.

5.1 The Ningaloo Reef Structure and Evolution

The Ningaloo Reef has been divided into three sectors based on bathymetric characteristics (Hearn et al., 1986). The northern sector from Northwest Cape to Point Cloates (120 km) has a narrow (less than 3 km wide) lagoon parallel to a straight coast. The shelf here is about 10 km wide and shore parallel. The central sector from Point Cloates to Point Maud (50 km) has a 6 km wide lagoon and predominantly unbroken reef with a major reef break to the south near Point Maud. The southern sector from Point Maud to Gnarraloo Station (90 km) is characterised by highly segmented/scattered reef structure and a very narrow (1 km wide) lagoon.

The Ningaloo Reef is 280 km long and forms a segmented barrier which is cut by reef passes causing the development of a distinctive lagoonal current pattern (Sanderson, 2000), described in section 3.3. The reef system has a broad reef flat up to 100 m wide, which outcrops close to mean low water spring tide and the reef crest is emergent for 10% of the year (Hearn et al., 1988). The seaward margin is steeply sloped and drops to a water depth of over 100 m only 5 km from the reef crest (Collins et al., *2002*). At high tide the reef crest is frequently overtopped by tide and wave action. The lagoon to landward of the reef flat is up to 6 km wide and has small patch reefs. There is typically a deep channel midway across the lagoon.

Collins et al. (2002) dated and described the development of the northern Ningaloo Reef. A series of seismic lines and cores were used to date both the Last Interglacial and the modern reef. Core dates came mostly from one core, Tantabiddi II that intersected Last Interglacial Pleistocene reef below a disconformity at 18m below sealevel and continued for a further 11 m. The top of this unit has a U series age of 115 ka BP and the base 119 ka BP. This suggests that the reef beneath the modern crest grew towards the end of the Last Interglacial highstand, later than most other Interglacial reefs (Collins et al., *2002*). A maximum reef thickness of 18m was predicted for the overlying Holocene reef. The base of the Holocene reef has a U series age of 7.57 ka BP and is composed of relatively homogeneous robust coral framestone, often bound by encrusting coralline algae (Collins et al., *2002*).

5.2 Terrestrial Geomorphology

The geomorphology of the dune and cuspate spit coast (D A Lord & Associates Pty Ltd, 2000) adjacent to the Ningaloo Reef reflects the three dominant processes involved in the evolution of the coast; lagoon circulation, sealevel variation and wind action. All four mapped areas are contained within the dune and cuspate spit coast but have specific features; they are summarised below in terms of their general geomorphology and dominant geomorphic features. Figure 1-2 shows the location of mapped areas. This chapter is intended to be read in conjunction with the supporting maps (A-D) as well as Figure 5-1 to Figure 5-4.

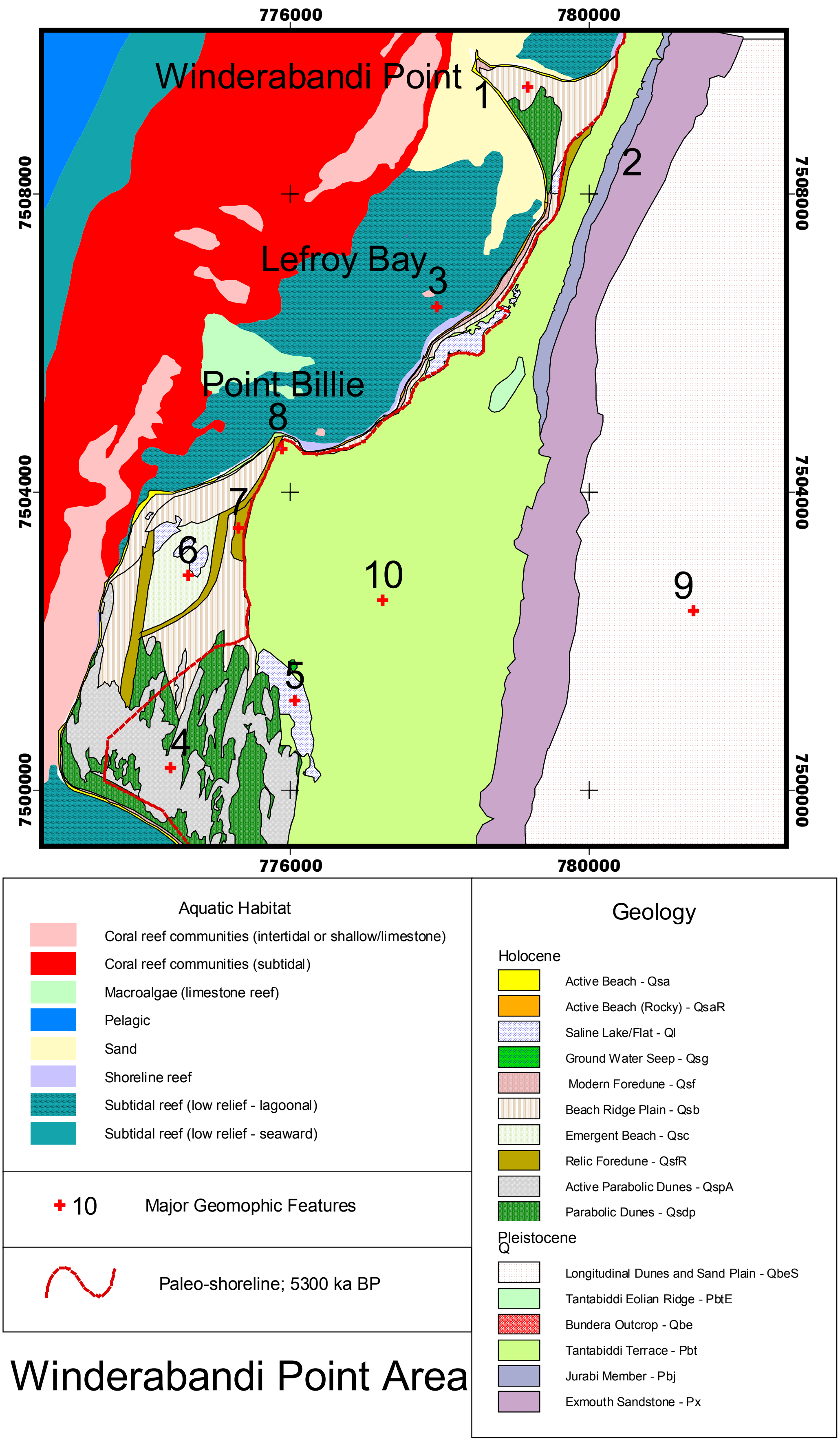


Figure 5-1. Winderabandi Point area (area A) major geomorphic features; see 5.2.1 for description.

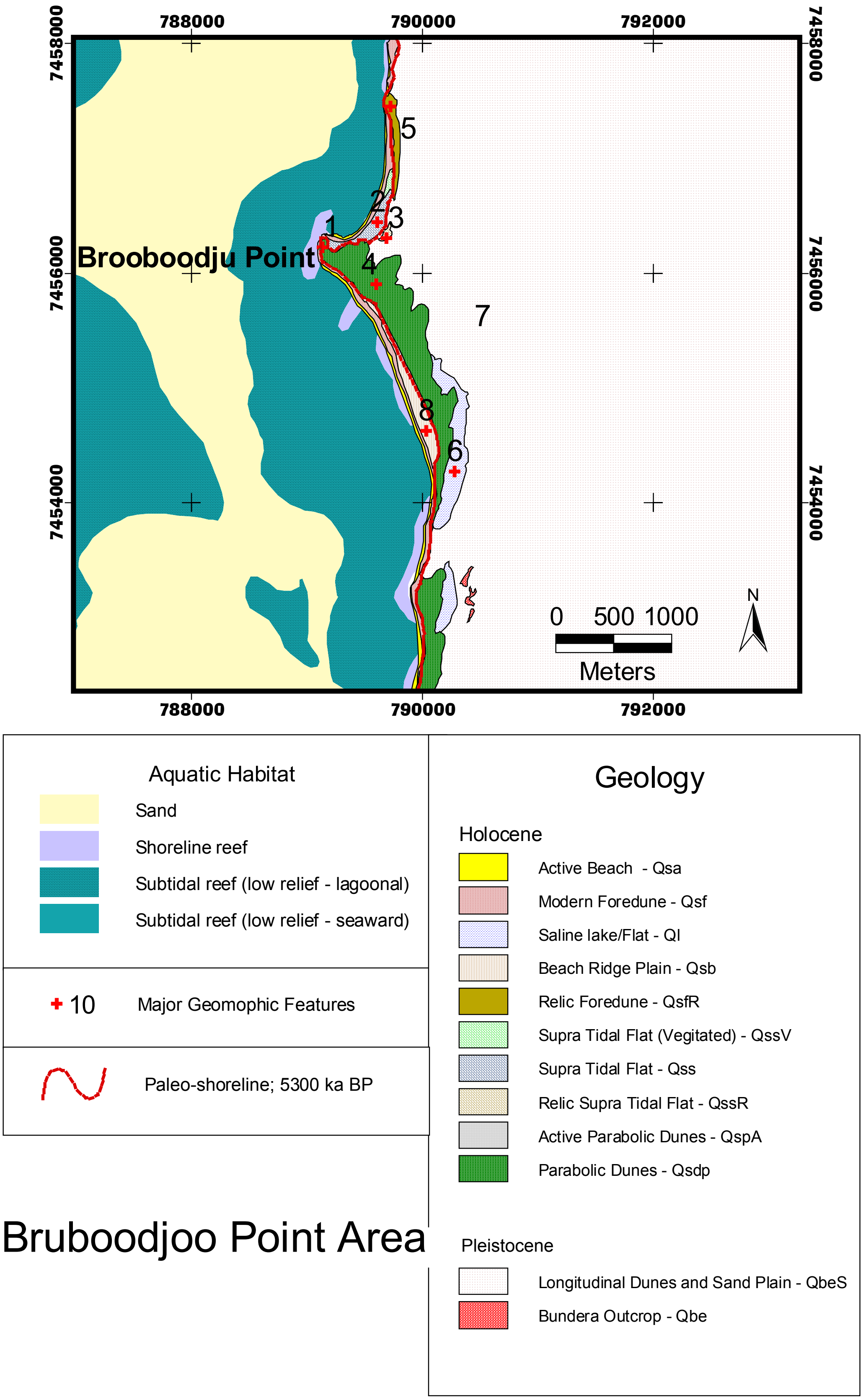


Figure 5-2. Bruboodjoo Point area (area B) major geomorphic features; see 5.2.2 for description

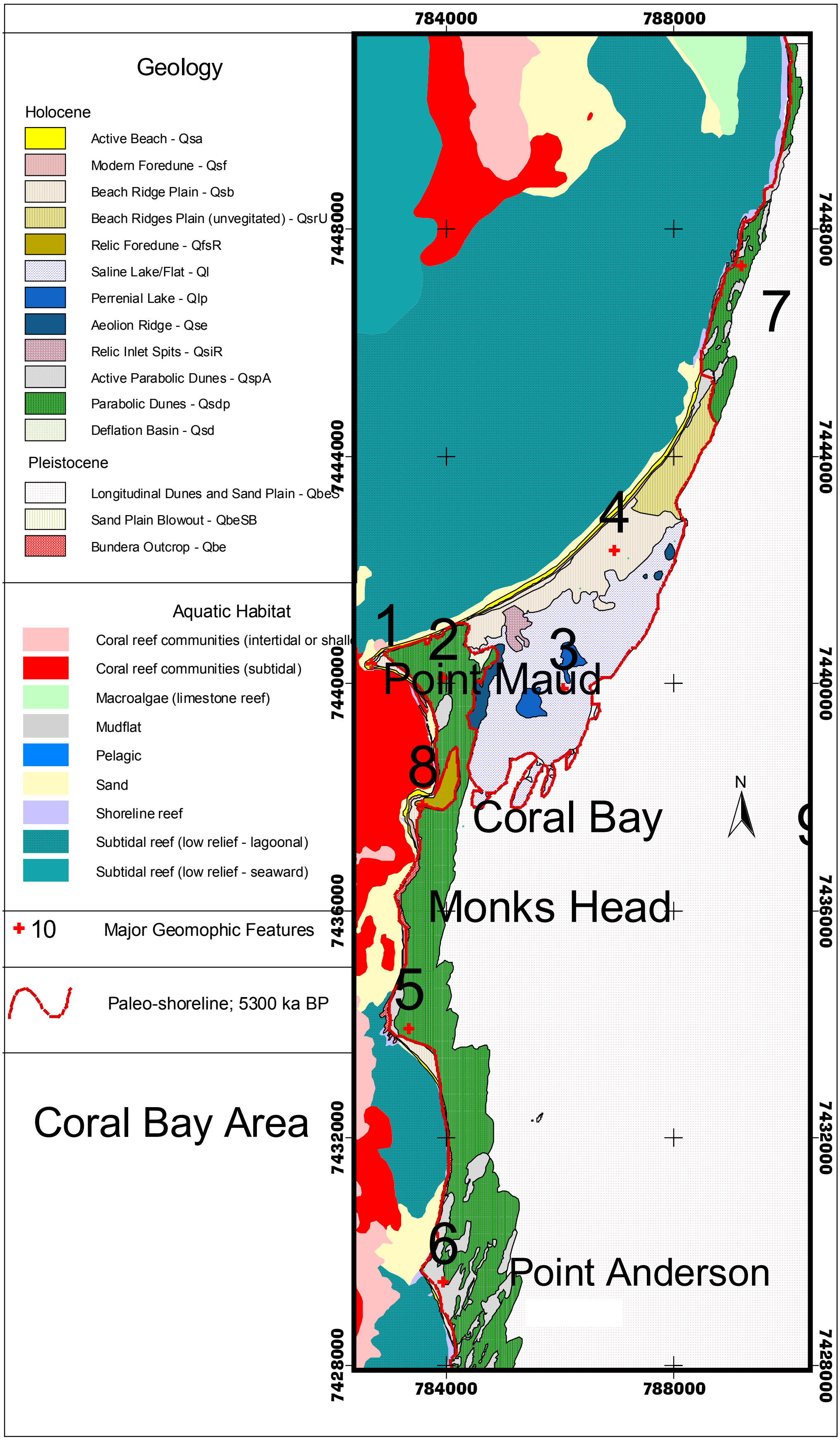


Figure 5-3. Coral bay area (area C). major geomorphic features; see 5.2.3 for description

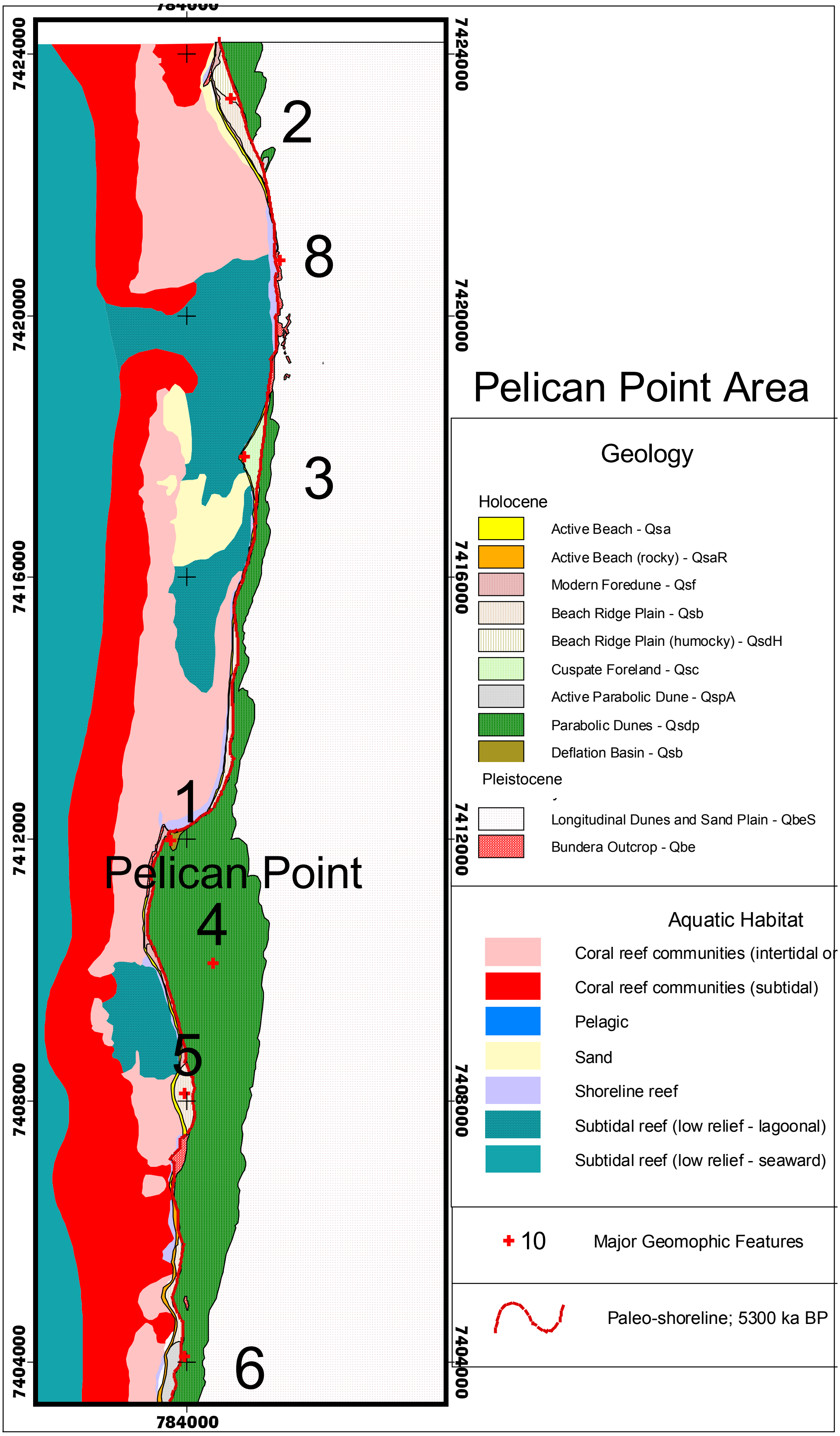


Figure 5-4. Pelican Point area (area D) major geomorphic features; see 5.2.4 for description

5.2.1 Winderabandi Point Area (Area A)

Area A is characterised by a limestone hinterland, including terraced Cape Range foothills, adjacent to; a sandy cuspate foreland in the north, a central rocky bay, a relic coastal sequence of linear dunes and a large parabolic due field and in the south.

Winderabandi Point (1; Figure 5-1 and Figure 5-6) is the dominant headland in the north of area A. This point is a cuspate foreland that has been modified by the development of parabolic dunes prograding from the south and is composed of a linear dune plain and parabolic dunes (maximum height of 15 m) overlying a limestone core. The bay immediately to the north is almost entirely floored by subtidal reef, whereas the immediate southern substrate has a sandy veneer. Winderabandi Point itself abuts the Tantabiddi Terrace and extends 1.8 km into the lagoon. This feature has a major effect on lagoon currents by constricting lagoon circulation to a narrow gap between the point and reef crest.

The largest areal component of area A is composed of Tantabiddi Terrace (10; Figure 5-1 and Figure 5-6). This paleo-reef and lagoonal limestone is covered by a variable thickness of red colluvial soils and unconsolidated calcareous sands. It is almost entirely flat with the only undulations associated with relic-dune ridges and karst sinkholes (see Figure 5-1 D).

Area A includes the southern extent of Cape Range, which rises to 100 m and consists of terraced limestone. The range decreases in elevation southward and has no surface expression immediately south of area A (2; Figure 5-1).

Lefroy Bay (3; Figure 5-1 and Figure 5-5) is a shallow bay with rock pavement shorelines and sparse patch reefs in the lagoon that is floored by subtidal reef and thin sand veneers. All beaches along the bay are rocky with frequent limestone outcrops and intertidal limestone pavement, as shown in Figure 5-1 A.

A large parabolic dune field is present to the south (4; Figure 5-1). Around 50% of the dune field is denuded, and dunes are actively prograding to the north. The maximum dune height is 35 m.

Three saline flats exist in area A. The northern flat is an emergent marine embayment stranded by sealevel regression. The central saline flats are low points in a widespread emergent beach unit. The southern flat is a local depression that has developed into a drainage basin due to the permeability barrier at the boundary of the limestone plain and elevated parabolic dune terrain to seaward (5; Figure 5-1).

The area immediately north of the parabolic dune field is composed of a regressive system of relic coastal features (6; Figure 5-1). These features include emergent beach, linear dune plains and relic-foredunes. The emergent beach unit has little to no undulation and includes saline flats. The beach ridge plains are composed of successions of prograded beach ridges 1-3 m high. Well vegetated relic-foredunes delineate at least two separate relic shorelines and have a maximum elevation of around 10 m (7; Figure 5-1).

Point Billie is a limestone headland with 1-2 m elevated, Last Interglacial, wave cut platforms. The outcrop includes large examples of fossilised coral heads in the paleo-reef composed of Tantabiddi Member (8; Figure 5-1, Figure 5-5 and Figure 5-1 C).

The area to the east is a large expanse of red longitudinal dunes and sand plains. This Early Quaternary unit extends for over 100 km inland along the Gascoyne Coast and has been attributed to the desertification of the hinterland during the Early Quaternary (Wyrwoll et al., 1992) (9; Figure 5-1 and Figure 5-1 B).

5.2.2 Bruboodjoo Point Area (Area B)

Area B is characterised by an undulating limestone hinterland with a thin colluvial cover, a narrow coastal strip of Holocene dunes and a limestone headland with associated supra-tidal flat.

Bruboodjoo Point is a limestone headland that protrudes into the lagoon. The point itself is composed of a Bundera Limestone core and has been prograded over by parabolic dunes (1; Figure 5-2). A supra-tidal flat is located adjacent to the modern foredune of the bay created by Bruboodjoo Point. This low-lying feature abuts the parabolic dunes to the south and includes a well-vegetated section to the north. The flat is almost 1 km long and 100 m wide in its central area (2; Figure 5-2 and Figure 5-1 B). A relic supra-tidal flat is located to the east. This flat is raised at least 2m above sealevel (3; Figure 5-2). A prominent relic-foredune extends from the northern end of the supra-tidal flat. This feature rises to 10 m to form a ridge and delineates a relic-shoreline (5; Figure 5-2).

The parabolic dune plain to the south of Bruboodjoo Point has a maximum height of 21 m and extends 400m inland. The dunes are well vegetated by both grassland and minor scrub (4; Figure 5-2). Two low-lying regions to the south of Bruboodjoo Point have developed as saline flats adjacent to the parabolic dunes. Relic-shorelines including small cliffs exist on the east side of the saline flats (6; Figure 5-2). Area B is dominated in the east by a large expanse of longitudinal dunes and sand plains overlying undulating Bundera Limestone.

5.2.3 Coral Bay Area (Area C)

The Coral Bay area (area C) is characterised by substantial coastal limestone outcrop and a narrow Holocene coastal fringe in the north, a large stranded marine embayment, beach ridge plain and composite spit in the cental part, and embayment fill, linear dune plains and cliffed coast in the south.

The most obvious feature of the coastline in the southern half of the Ningaloo Reef (and area C) is Point Maud. The point is a composite spit composed of parabolic dunes with a narrow extent of beach ridges and modern foredunes (1; Figure 5-3). The highest point is Maud Hill (31m). The parabolic dunes have a varying level of vegetation cover but are predominantly only covered in grassland or minor scrub and includes a large active parabolic dune.

The most northerly 6 km of area C in characterised by a narrow parabolic dune plain and significant coastal outcrop. The parabolic dunes in this area have relatively low vegetation cover and extend for a distance of around 300 m inland from the beach (7; Figure 5-3).

The parabolic dune plain extends the entire length of area C. The plain is up to 1 km wide with a maximum dune height varying from 17 to 55 m (2; Figure 5-3 and Figure 5-2 C). During fieldwork, in June 2002, it was noted that the parabolic dunes to the south close to Point Anderson had been severely denuded by a recent fire and the only vegetation cover was provided by buffel grass. This is a concern as this grass was only present in such abundance due to unseasonable recent rainfall. The coast between Point Anderson and the beach ridge plain to the north is a limestone cliffed coast with cliffs reaching 10 m (see Figure 5-2A).

A large stranded marine embayment is located to the east of the Coral Bay townsite. The area now exists as a saline flat/lake including perennial lakes. The saline flat/lake is 6 km long (north-south) and 1.8 km wide (east-west). The area has minor cover of salt tolerant vegetation (3; Figure 5-3). The region to the north of the saline flat/lake is a large beach ridge plain. The plain is composed of a sequence of prograded beach ridges forming a linear, undulating topography. The unit has a medium to low vegetation cover predominantly of grassland and scrub (4; Figure 5-3).

Four kilometres south of the Coral Bay Townsite, the coastline is embayed to the east. A beach ridge plain has developed here and significant limestone outcrop occurs. A large area of denuded, active dune has developed here, that appears to be initiated or exacerbated by high vehicular traffic use (5; Figure 5-3).

Point Anderson is the prominent point to the south of area C. This point is composed of limestone outcrop that has initiated and controlled the evolution of the point. The parabolic dune plain that overlies the point is highly denuded and includes numerous active dunes (6; Figure 5-3).

Coral Bay townsite is located on a relic-foredune plain, beach ridge plain and the swales of parabolic dunes. Large relic-foredunes and beach ridges form the "half heart" coastline of Bills Bay (8; Figure 5-3). The coastal units in area C area backed to the east by the large expanse of longitudinal dunes and sand plains (9; Figure 5-3 and Figure 5-2 B).

5.2.4 Pelican Point Area (Area D)

Area D is characterised by an undulating limestone hinterland with a thin colluvial cover, a predominantly narrow coastal strip of Holocene dunes, but includes a wide parabolic dune field associated with a limestone headland and two linear dune plains.

Pelican Point itself is a limestone headland overlain by a large parabolic dune field. The immediate coast along the length of the point is composed of low angled beds of consolidated beach sediments. The limestone beds are highly disrupted, presumably by Tropical Cyclones (1; Figure 5-4). The prominent geomorphic feature in the north of area D is a beach ridge plain including hummocky beach ridges and limestone beach outcrop. This area abuts a relic-shoreline to the east that includes relic-sea cliffs (see Figure 5-2 D and E). This beach ridge plain can be separated into two units; linear beach ridges and hummocky beach ridges. The formation mechanism of the hummocky unit is unclear, but may be the result of the remobilisation of linear beach ridges after scattered vegetation has become established, creating patches of raised sand, as opposed to continuos ridges else ware. The modern foredune adjacent to the limestone beach outcrop is very high (10 m) and steep. This is a result of this beach facing the primary wind direction during Tropical Cyclones (2; Figure 5-4).

The best example of a cuspate foreland in the four mapped areas is located in area C. The cuspate foreland is composed of a series of curved beach ridges with low relief of 1-3 m and medium to high shrub and grassland cover (3; Figure 5-4). The parabolic dune plain in area D is particularly wide (up to 2 km) in parts, with a maximum dune height of around 25 m. Only a very sparse cover of grass and minor scrub is present on these dunes (4; Figure 5-4).

A second beach ridge plain exists in the south of area D. This series of prograded beach ridges that extend from a relic-shoreline have a medium cover of grass and scrub with a denuded foredune adjacent to the beach (5; Figure 5-4). The southern end of area D is characterised by large amounts of limestone outcrop that extends for 300 m offshore and effectively replaces reef crest as the lagoonal barrier. The limestone outcrop creates rocky beaches with only a thin veneer of lagoonal sediments covering it between shore and the barrier 300m offshore (6; Figure 5-4).

A 2.7 km long section of cliffed of coast exists in this area. Up to 4 m high cliffs are composed of eolian components of Bundera Limestone (8; Figure 5-4). Here the longitudinal dunes and sand plain abut the ocean (see Figure 7-4).

Figure 5-5. South half of a panoramic photo of area A. The image was shot from the Jurabi Terrace facing west. The numbers refer to 5.2.1. and Figure 5-1. South is to the left.

Figure 5-6. North half of a panoramic photo of area A. The image was shot from the Jurabi Terrace facing west. The numbers refer to 5.2.1. and Figure 5-1. South is to the left.

A. Intertidal limestone pavement in Lefroy Bay (area A) at low tide.

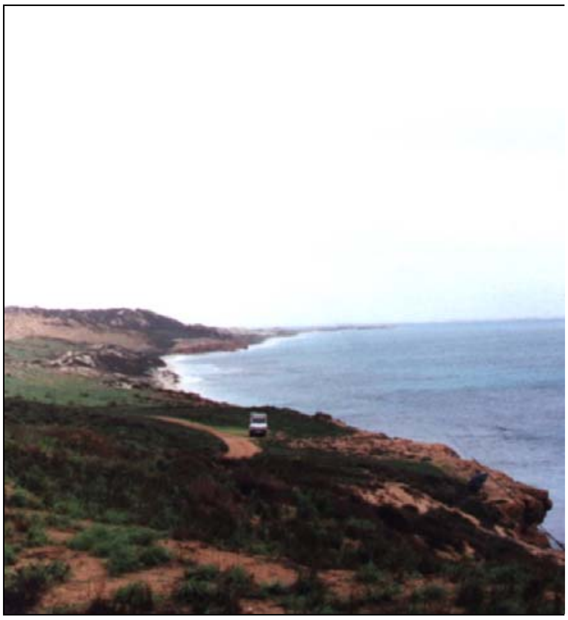
B. Supra-tidal flat adjacent to Bruboodjoo Point in area B. The photograph was taken from the relic supratidal flat (that is raised by approximately 2m) facing west.

C. Last Interglacial coral head in Tantabiddi Member at Point Billie area A. Compass for scale.

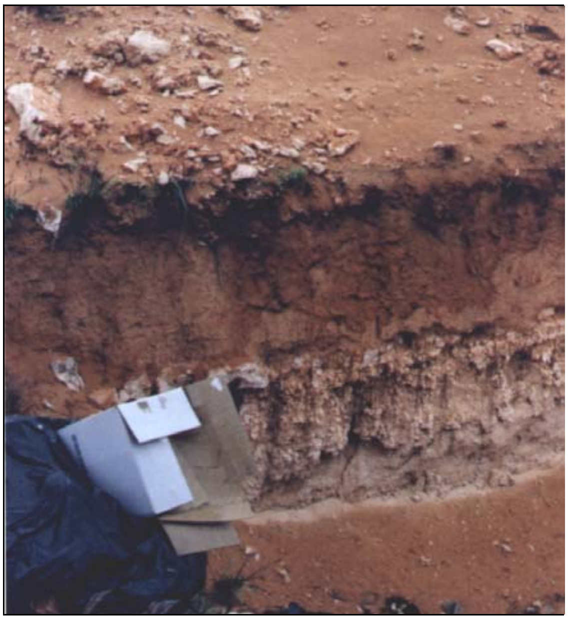
D. Kast sinkhole in Tantabiddi Member close to Cape Range (grid ref. 779500, 7506000)

E. Active parabolic dune just south of area B. Note the lush grass cover caused by recent heavy rain.

Figure 5-1. Photographs of geomorphological features areas A and B.



A. Rocky cliffed shoreline north of Point Anderson in area C. Point Anderson is in the background.



B. A shallow trench at the Coral Bay tip showing the sand plain stratigraphy of calcrete soils overlain by red colluvium.

C. Steep face of a parabolic dune 1 km east of Mauds Landing in area C. Note the patchy vegetation cover and unsustainable access track.

D. View of beach ridge plain on the left and parabolic dunes on the right in area D. See 2 on Figure 5-4

E. Coastal sequence in area D including relic-sea cliffs on the right, prograded beach ridges (centre), active beach and lagoonal deposits (left) and parabolic dunes in the background.

Figure 5-2. Photographs of geomorphological features, area C and D.

6 LAND SYSTEM UNITS

Land system units are delineated by geological boundaries, and then further defined by the unit's substrate capability and land use characteristics. Land system units are therefore interchangeable with geological units, but include important land management information. Table 6-1 describes the characteristics of the 27 land system units present in the four mapped areas.

The substrate capability index (SCI) is defined as "The capacity of a land unit's substrate to withstand environmental impacts from natural processes and/or land use activities" see section 1.2.4.

Table 6-1. Geologic and land use features of the 27 units present in the four mapped areas adjacent to the Ningaloo Reef.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Active Beach	Qsa	Variable width 1-20 m. Low to medium angle beach face. Predominantly composed of medium to coarse-grained calcareous sand. Some rubble beach faces due to tropical cyclone impacts. No vegetation.	1	Active wind and wave erosion. Unconsolidated sands. Highly variable width and depth. Unit is reworked by tidal and wave action (predominantly depositional/ replenishing system).	Predominantly little to no vehicle use. Areas of coastal access have high vehicle use eg. where inland routes are either non-existent or blocked.	Turtle nesting sites are present on north side of Point Maud to the north. This is a high use beach for access to the oyster reef to the north.
Active Beach (rocky)	QsaR	Variable width 1-6 m. Low to medium angle beach face. Predominantly composed of medium to coarse calcareous sand but with significant rock outcrop. No vegetation. Includes shoreline, intertidal rock pavements. Rock unit = Bundera Limestone and Tantabiddi Member.	2	Active wind and wave erosion. Unconsolidated sands and consolidated limestone. Highly variable width and depth. Unit is reworked by tidal and wave action (predominantly depositional/ replenishing system). Rock platforms often exist below a sandy beach with frequent outcrop.	Predominantly little to no vehicle use.	A rocky beach was distinguished from the active beach unit as being composed predominantly of limestone outcrop as opposed to unconsolidated sand.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Modern Foredune	Qsf	Single linear dune parallel to coast with high sloped dune face. Height from 1-10 m and width from 1-20m. Adjacent to the active beach. Very low (hummock grassland) to nil vegetation cover	1	Unstable dune face. Unconsolidated sands. Little vegetation. Active wind erosion. Wave erosion during storm, tropical cyclone and tsunami events.	Commonly eroded in high use zone by access to the beach or camping sites situated in the foredune itself.	A coast that faces the prevailing wind during Tropical Cyclones (north) typically develops high foredunes.
Beach Ridge Plain	Qsr	Low to medium gradient linear dunes. Commonly forming beach ridge plains. Dunes range in height from 1-3 m and width from 1-7 m. Low to medium (grassland and shrubland) vegetation cover. Prograded from highstand paleo-shoreline or seaward face of parabolic dunes to the modern shoreline.	2	Unconsolidated calcareous sand. Predominantly low sloped ridges. Predominantly low vegetation cover.	Utilised for substantial access and camping sites in high use zones.	Where large denuded/un vegetated areas exist they have been mapped separately.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Beach Ridges (Hummocky)	QsrH	Low gradient hummocky dune plain. Dune height from 1-3 m, width from 1-7 m. Prograded from highstand paleo-shoreline (+2 m) to modern shoreline. Medium (shrubland) vegetation cover. Composed of isolated clumps of shrubland.	2	Unconsolidated calcareous sand. Predominantly low angle ridges. Medium vegetation cover. Composed of isolated clumps of shrubland.	High use zone with an uncontrolled network of tracks developed throughout the area.	This is a localised unit in area D. The main access north south through this unit needs to be marked to restrict access across it.
Beach Ridges (Un-vegetated)	QsrU	Medium to high gradient linear dune forming beach ridge plains. Height from 1-3 m and width from 1-7 m. Prograded from highstand paleo-shoreline to modern shoreline. No vegetation cover. Some small blowouts in beach ridge plain.	1	No vegetation. Unconsolidated sand. Denudation probably caused by stock damage. Small blowouts currently formed.	No vehicular access. Private access is restricted by Cardabia Station Significant stock damage.	Localised unit in area C.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Cuspate Foreland	Qsl	Composed of curved linear ridges forming a foreland. Ranges in height from 1-3 m and width from 1-7 m. Medium to high shrubland cover. Includes narrow modern foredune.	2	Unconsolidated sand. Medium vegetation cover. Seaward face exposed to wind and wave action.	Medium level of vehicle access and camping use.	Localised unit in area D. Access to the cuspate foreland north of Pelican Point has been restricted by Warroora station.
Perennial lake	Qlp	Perennial lakes in low point of saline flats. Variable in size due to rainfall. No vegetation. Very saline water.	1	Saturated unstable substrate.	None	Localised unit in area C.
Sand Plain Blow out	QbeSB	Active blowouts in sand plain. Composed of unlithified cover on Bundera Limestone. Prograding northward.	1	Blowouts form predominantly as a direct result of access and stock land use. Also formed due to fire caused vegetation loss.	The majority are intersected by access tracks.	Majority of blowouts are initiated by access tracks.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Parabolic Dunes (Active)	QsdpA	Rounded parabolic dunes with high gradient curved prograding faces. 3 to 40 m high, up to 300m wide. Prograding northward for up to 500m. Very minor (grass) to no vegetation cover. See appendix 1 for a detailed petrographic description of this unit and Figure 6-1 E for a thin section image.	1	Currently prograding, Can affect adjacent units. Basically no vegetation.	None	
Saline Flat/Lake	Ql	Low lying saline flats. High salinity waters and sediments. Composed of marine sands and overlying saline soils and algal crusts. Marine metahaline shell assemblages present. Variable thickness over existing surface (usually Bundera) of 0-3 m. Minor salt tolerant vegetation cover.	1	Becomes muddy very quickly after rain. Can flood during more extreme rain events.	Heavily utilised for access.	The large saline lake east of Coral Bay is heavily used for ultra-light airstrip, road material pits, station access and stock watering.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Supra-tidal Flat	Qss	Low-lying saline supra-tidal flats. High salinity. Composed of marine sands and overlying saline soils and algal crusts. Variable thickness over existing surface (usually Bundera Limestone) of 0-≈3 m. Minor salt tolerant vegetation cover. Adjacent to coastal foredune.	1	Tsunami risk due to proximity to coast and low elevation. Saline Flood risk in extreme precipitation event.	Heavily utilised for access and camping.	The only example of unit exists at Bruboodjoo Point. This is a very popular camping area with up to 20 separate sites present.
Aeolian Ridge	Qse	Rounded mounds and ridges located in saline flat. Rounded mounds have diameter of 50-200 m and 1-6 m high. Composed of clean quartz sand. Medium to high (shrubland) vegetation cover.	3		Only one main access track crosses the unit.	Localised unit only located in large saline flat to the east of Coral Bay.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Parabolic Dunes	Qsdp	Rounded parabolic dunes with high gradient curved prograding faces. 3 to 40 m high. Very minor (grassland) to high (shrubland) vegetation cover. Form regional dune fields. Stained red in colour from the dust of the inland desert dunes. See 0 for a petrographic description of the unit.	2	Steep dune faces. In some areas vegetation is badly affected by fire. Have been stable for considerable time. Dune cores are frequently partially consolidated.	Only low to medium use due to the steep slopes of the dune faces.	This unit is the major geomorphic feature of the immediate coast in the southern half of the Ningaloo Reef. Dunes that have only a sparse cover of buffel grass due to fire damage are a concern due to the sporadic nature of that ground cover.
Deflation Basin	Qsd	Deflation basin formed by progradation of parabolic dune. Low elevation. Very high shrubland cover.	3		Very little if any land access use.	

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Emergent Beach	QscR	Low elevation plain. Little to no undulation. Composed of beach derived carbonate sand. Water table is 1m below surface. Medium to high vegetation cover (predominantly buffel grass). Incorporates some small saline flats.	2	Saline sandy substrate. Flooding risk in extreme rain events.	Only one main access track crosses this localised unit.	Localised to the south of Point Billie south of Winderabandi Point.
Relic-Foredune	QsfR	Large single linear dunes tracing paleo shorelines. 5-6 m high and 10-20 m wide. Medium gradient dune face. Very high shrubland cover.	3	Sandy but well vegetated.	Only one main access track crosses this localised unit.	Localised to the south of Point Billie south of Winderabandi Point
Relic-Inlet Spits	QsiR	Splayed group of low ridges protruding from linear beach ridge plain into saline flat. Up to 2 m high. Low gradient dune face. Low to medium (grassland and shrubland) vegetation cover.	2	Unconsolidated but low gradient.	Only two access tracks cross this localised unit.	Localised unit located on the saline flat to the east of Coral bay.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Relic Supra-tidal Flat	QssR	Relic supra-tidal flat raised by up to 2 m from sealevel. Saline flat composed of gypsiferous carbonate sands. Low cover of salt tolerant vegetation.	2	Saline sand to gypsiferous muddy sands.	Intersected by main access to Bruboodjoo Point (localised unit).	Localised unit located on the saline flat to the east of Bruboodjoo Point.
Ground Water Seep	Qsg	Small rocky area covered in a thick scrub of Acacias.	3		Shade and feed utilised by stock.	
Tantabiddi Aeolian Ridge	PbtE	Ridge 6 m high composed of heavily calcretised limestone (calcareous grainstone). Parallel with paleo shoreline. Medium gradient paleo dune face. Very little vegetation cover.	4		No land use.	

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Longitudinal Dunes and Sand Plain	QbeS	Lage expanse of red longitudinal dunes and sand plains overlying heavily calcretised Bundera Limestone (predominantly eolian Pleistocene sandy limestone). 0-≈ 4 m, cover of red soils and calcareous sand, including calcrete layers and nodules. Bundera Limestone often outcrops (both calcretised and non calcretised) usually at high points such as dune tops. No to medium vegetation cover, predominantly grass plains.	3	Cover of unconsolidated material has high potential to blow out. Low vegetation cover.	Sparse major access tracks (including sealed roads) and Minor tracks servicing localities such as dumps, pits and Stations.	This unit is very extensive across the Gascoyne region. The unit extend from the base of Exmouth Gulf to Carnarvon.
Bundera Limestone Out-crop	Pbe	Coastal and sand plain outcrops. Composed of consolidated limestone. Forms both rock platforms and cliffed coast. Cliffs vary from 1-6 m in height. Provides rocky intertidal substrates and commonly forms the “core” to headlands. Predominantly eolian limestone but with minor marine	5	Occupies only small areas.	The unit is utilised for access if tracks intersect it.	outcrops are coastal cliffs, relic shorelines or exposed paleo dune crests.

UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
		components. See appendix 1 for descriptions of the various components of Bundera Limestone.				
Tantabiddi Terrace	Pbt	Last Inter Glacial Limestone paleo reef /lagoon system formed over wave cut terrace. Over lain by 0-≈3 m of unconsolidated soils and calcareous sand. Frequently outcrops on coast. Medium to very high cover of vegetation including groves of Acacias. Contains karst depressions, where karst voids have collapsed close to the Cape Range.	4	A lime stone pavement under laying a varying cover of unconsolidated soil and calcareous sand. Well vegetated in parts with groves of Acacias common.	Main north-south access tracks (the Coral Bay road) are located on this unit.	Small creeks have developed across this unit. These creeks would be the focus of runoff during extreme rain events and should be considered a hazard for land use.
Jurabi Member	Pbj	Terraced rock outcrop. Height ca 10-20 m width 50-100 m. Composed of well-consolidated reefal limestone. Sparse grassland and sporadic shrubland cover. Forms the foothills of the Cape Range.	5	Consists of elevated rocky terrace; coast parallel.	Very minor track access.	

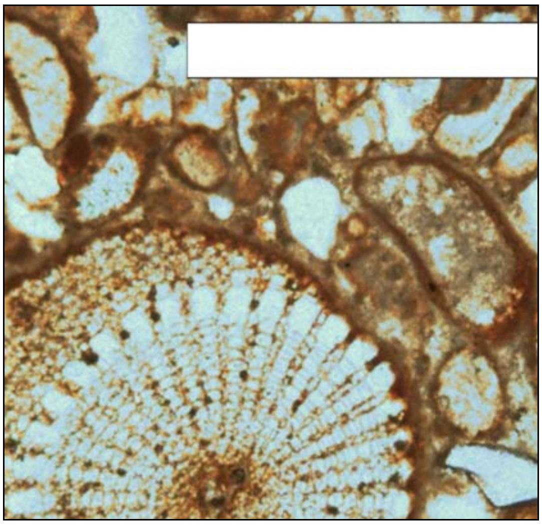
UNIT		DESCRIPTION	SCI	SUBSTRATE CAPABILITY COMMENTS	LAND USE PATTERN	COMMENTS
Exmouth Sandstone	Px	Limestone rock outcrop part of Cape Range. Height ca 100 m. Composed of consolidated sandy limestone.	5	Very steep and gullied topography.	Very minor track access	

6.1 Land System Unit Lithology

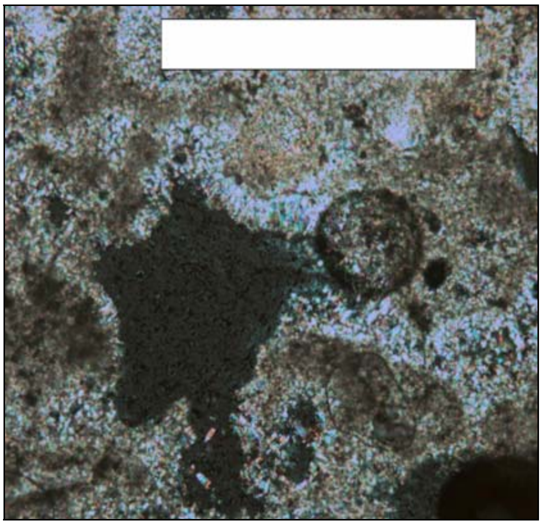
The lithology of the land system units adjacent to the Ningaloo Marine Park can be grouped by equivalent lithologies. These groups are partly synonymous with the coastal evolution stages that are the consequence of Holocene sealevel changes described in section 7.2 and Figure 7-2 .

Table 6-2. Lithology summaries for the land system units adjacent to the Ningaloo Reef.

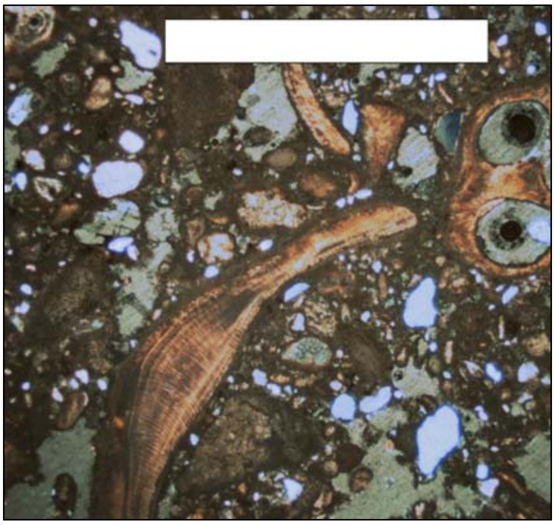
Lithologic group	Included Land System Units	Lithology
Stage 4&5 Progressional and modern beach deposits	Active Beach Active Beach (rocky) Modern Foredune Beach Ridge Plain Cuspate Forelands Modern Parabolic Dunes	Medium to fine grained calcareous sands. Poorly sorted and well rounded. Composed of open marine assemblage, predominantly calcareous algae with minor molluscan, echinoid and coral fragments and benthic foraminifera. Rock beaches includes element of pre holocene limestone. Beach deposits are commonly coarser than dune deposits.
Stage 3 Highstand marine deposits	Supratidal Flat Saline Flat/lake	Shelly open marine to metahaline and beach facies calcareous sands overlain by gypsiferous sands /muds and fenestral algal mat. Composed of predominantly calcareous algae and pelletal sediment with minor molluscan, echinoid and coral fragments and benthic foraminifera; including fragum, hemicardium, gastropods and bivalves.
Stage 2 Transgressive deposits	Parabolic dunes	Composed of open marine assemblage, predominantly calcareous algae with minor quartz, bryozoan, lithoclasts and coral fragments and benthic foraminifera. Rubified (reddened) by eolian dust from inland desert dunes.
Pre Holocene deposits	Bundera Limestone including; Tantabiddi, Jurabi and Exmouth members. Longitudinal dunes and sand plains.	The terrace members (Tantabiddi and Jurabi are composed of reefal framestone and lagoonal skeletal grainstone deposits. Bundera outcrops in the south are predominately heavily calcretised eolian limestone deposits composed of open marine assemblages and significant quartz. The seaward margins of the Bundera Limestone unit are composed of intertidal beach deposits. See Figure 6-1 for thin section images.



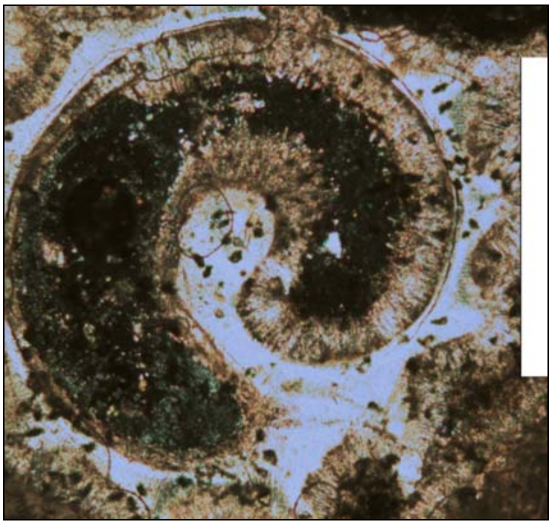
A. Sample S18Br. Echinoid spine and micrite rinds in Bundera Limestone. XP (bar=1.75 mm)



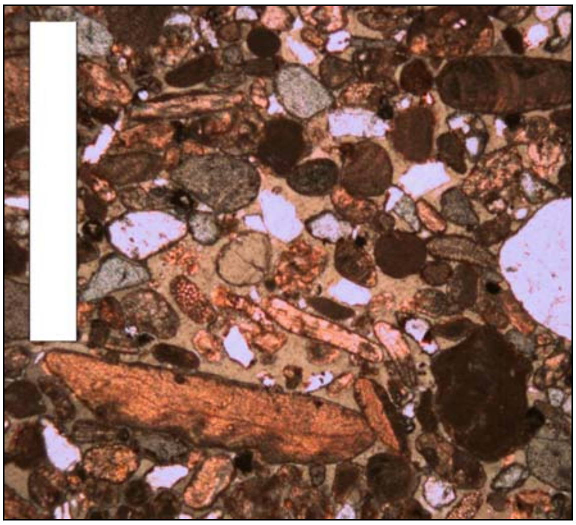
B. Sample S21Ch. Incipient aragonite on various skeletal grains in Bundera Limestone . XP (bar=0.45 mm).



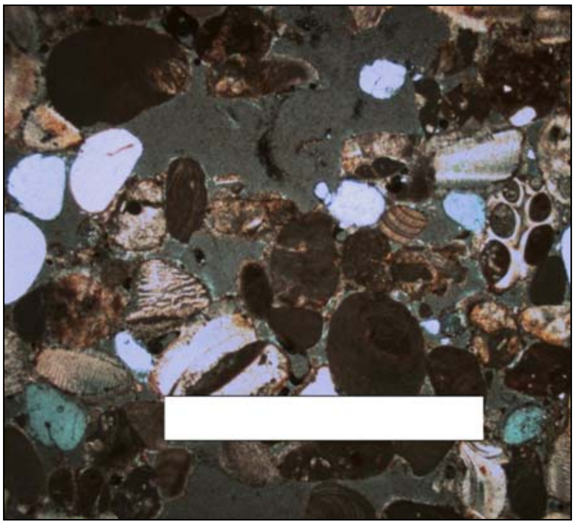
C. Sample S2aC Mollusc and gastropod in Bundera Limestone. XP (bar=3 mm).



D. Sample S28Da Incipient aragonite in gastropod in Bundera Limestone. XP (bar= 0.9 mm).



E Sample S31Dc. Open marine assemblage from active parabolic dune. XP (bar=1.75 mm).



F. Sample 34dl. Beach rock component of Bundera Limestone from Pelican Point. XP (bar=1.5 mm).

Figure 6-1. Thin section images of selected samples adjacent to the Ningaloo Reef.

7 QUARTERNARY COASTAL EVOLUTION

The coast adjacent to the Ningaloo Reef has developed during the Quaternary, predominantly in response to glacial sealevel changes. Last Interglacial and Plio-Pleistocene units formed the existing surface and initial topography for Holocene coastal development in response to a transgressive-regressive cycle of sealevel change in the Late Holocene.

7.1 Plio-Pleistocene Coastal Evolution

Plio-Pleistocene deposition adjacent to Ningaloo reef is an analogue of the modern reefal depositional system, overprinted with glacial sealevel variations and tectonic uplift. The major Plio-Pleistocene units are raised reef and lagoon deposits, stranded by a combination of sealevel regression and uplift due to anticline development. Plio-Pleistocene units present in the four mapped areas are, in increasing age; longitudinal dunes and sand plain, Bundera Limestone (including Tantabiddi, Jurabi and Exmouth Sandstone Members).

7.1.1 Cape Range Terraces Evolution

The emergent terraces on the western flank of the Cape Range provide a record of uplift of the range and sealevel change. These terraces were first described in detail by van de Graaff et al. (1976). This work distinguished four terraces, Tantabiddi, Jurabi, Milyering and Muiron (Exmouth Sandstone), see Figure 7-1. Each terrace is overlain by shallow marine and shoreline sediments and truncated to seaward by an erosion scarp, forming the corresponding members. The overlying members on the Tantabiddi and Jurabi Terraces constitute the Bundera Calcarenite and the members on the Milyering and Muiron terraces the Exmouth Sandstone (Figure 7-1). Only the youngest terrace, Tantabiddi, has been dated as the older terraces have undergone intensive recrystallisation. Fossil evidence has however been cited for dating the Jurabi Member. *Carcharocles Megladon* teeth have been found in the member that have a global temporal distribution of Miocene to Pliocene (Kendrick et al., 1991), so a Pliocene age is inferred for the terrace.

The Tantabiddi Member is a dominant feature of Quaternary geology on the coast plain adjacent to the Cape Range. It forms the basement to the coastal plain and the lagoon (frequently outcropping on the immediate coast). It also forms the substrate to the modern Ningaloo Reef (Wyrwoll et al., 1992; Collins et al., *2002*). Sanderson (2000) suggested that it forms the core of the prominent headland of Winderabandi Point. Late Pleistocene and Holocene dunes overlie the terrace at the coastal margin.

7.1.2 Pleistocene Desert Dunes Evolution

Pleistocene desert dunes dominate the inland regions of the coastal plain. These are an expression of significant climate change to more arid conditions. The dune plain extends from the base of Exmouth Gulf to the top of lake Macleod. These dunes are carbonate rich with a well developed profile of brown sand overlying pale sand with carbonate segregations and well developed calcrete in some areas. These dunes are frequently a significant feature of Quaternary geomorphological evolution of coastal regions, forming the barrier to Holocene drowning. Two Last Glacial maximum thermoluminescence ages, of 23.4 ±6.7 and 16.0 ±1.7 ka BP have been obtained from the dune area on the north of Cape Range peninsula (Wyrwoll et al., 1992). The dunes are therefore an indication of climatic aridity during the Last Glacial maximum.

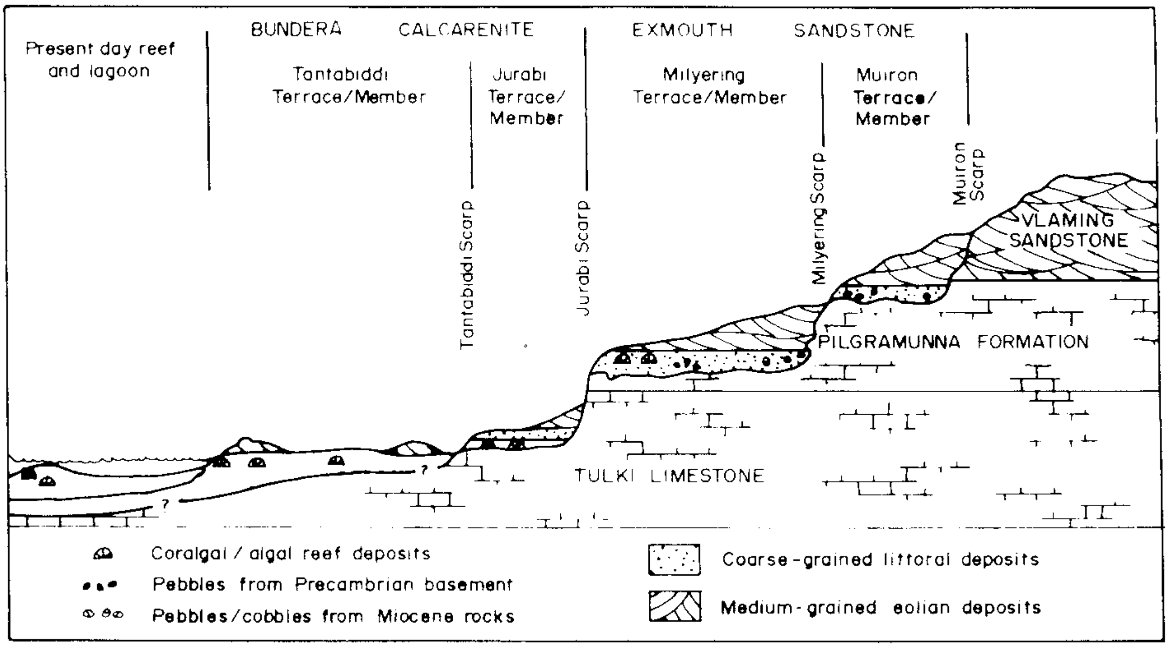


Figure 7-1. Uplifted coral reef complexes fringing the western flank of the Cape Range (after van de Graff, 1976)

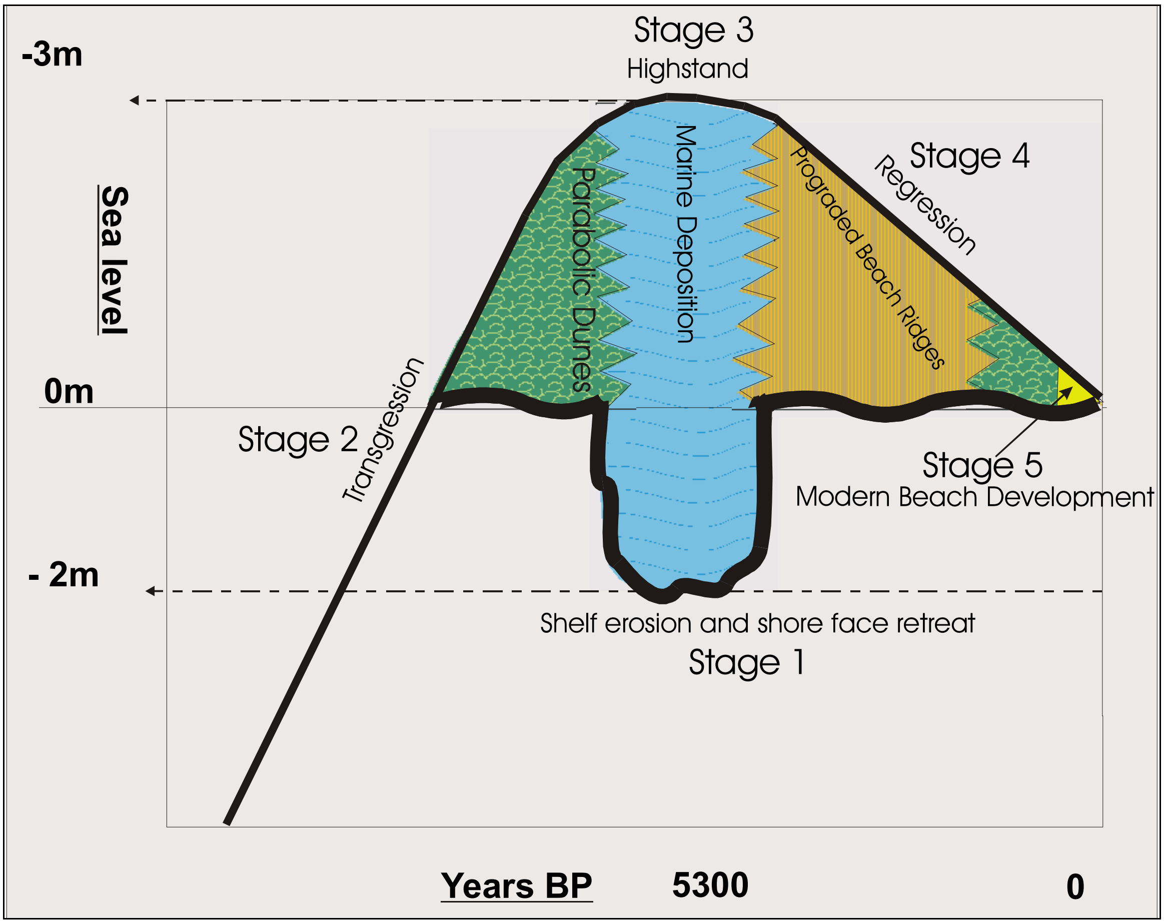


Figure 7-2. Holocene sealevel relationship to major coastal units adjacent to the Ningaloo Reef and the 5 Holocene coastal evolution stages.

7.2 Holocene Coastal Evolution

The Holocene (≈10 000 ka BP to present) evolution of the coastal plain adjacent to the Ningaloo Reef occurred in five stages; shelf erosion and shore face retreat, transgressive deposits, highstand deposits, regressive deposits and modern beach and foredune development. The first four stages are a direct response to the Late Holocene sealevel variations as shown in Figure 7-2, and the last is a consequence of the modern sedimentary system. Coastal morphology has developed as a consequence of sealevel change and it's interaction with initial coastal topography at the time of Holocene deposition. The four end-member coastal morphological types present adjacent to the Ningaloo Reef are; cliffed coast, embayment fill and beach ridges, parabolic dune coast and cuspate forelands.

7.2.1 Holocene Evolution Stage 1. Shelf erosion and shore face retreat

Following the Last Glacial Maximum sealevel (-120 m) at 20 ka BP, sealevel rose and had reached the current level by approximately 6000 ka BP (Collins et al., 1993; Eisenhauer et al., 1993; Wyrwoll et al., 1994; Baker et al., 2001; Yokoyama et al., 2001). During this period of shelf erosion and shoreface retreat, pre Holocene and early Holocene sediments where stripped off the Pleistocene shelf surface, remobilised and transported landward. The earliest record of onshore deposition is marine embayment fill, deposited in coastal depressions as the rising sealevel breached the coastal barriers and flooded small inland basins such as the Coral Bay "salt lake".

7.2.2 Holocene Evolution Stage 2. Transgressive deposits

The Late Holocene transgression continued after 6000 ka BP to a highstand of 2-3 m at 5300 ka BP. During this stage, the transgressive units preserved adjacent to the Ningaloo Reef were deposited. Local marine deposition continued through this stage as sealevel increased and local depressions developed from intertidal bays into shallow marine embayments. The main deposits in this stage are the nested parabolic dune fields that dominate much of the study region. Deposition started when the transgression allowed sediment to inundate coastal lowlands and continued during the early stages of the subsequent highstand. The sediment source for these dunes must have been much greater than that available at present as the modern parabolic dunes are not as large or as significant in coastal development. The source for the sediment would have been the pre Holocene and early Holocene sediments remobilised and continually reworked as coastal barriers as the shelf underwent erosional shoreface retreat. The stratigraphic positions of the parabolic dunes are shown in Figure 7-5.

7.2.3 Holocene Evolution Stage 3. Highstand Deposits

Transgression continued, drowning coastal lowlands and embayments, until approximately 5300 ka BP when a highstand of 2-3 m occurred. The length of the highstand is unclear but was probably in the order of 500-1000 years and was followed by a slow regression to present sealevel. The paleo shoreline exists to landward of all Holocene highstand and regressive units and is shown in Figure 5-1 to Figure 5-4 for each mapped area. The majority of marine embayment fill deposition would have occurred during this period and parabolic dune development would have continued as the increasing sealevel allowed progradation over sea cliffs, see Figure 7-2. A parabolic dune field in the Pelican Point area (area D) suggests deposition of parabolic dunes occurred during highstand, as it has prograded over a 3-4 m sea cliff see Figure 3-6.

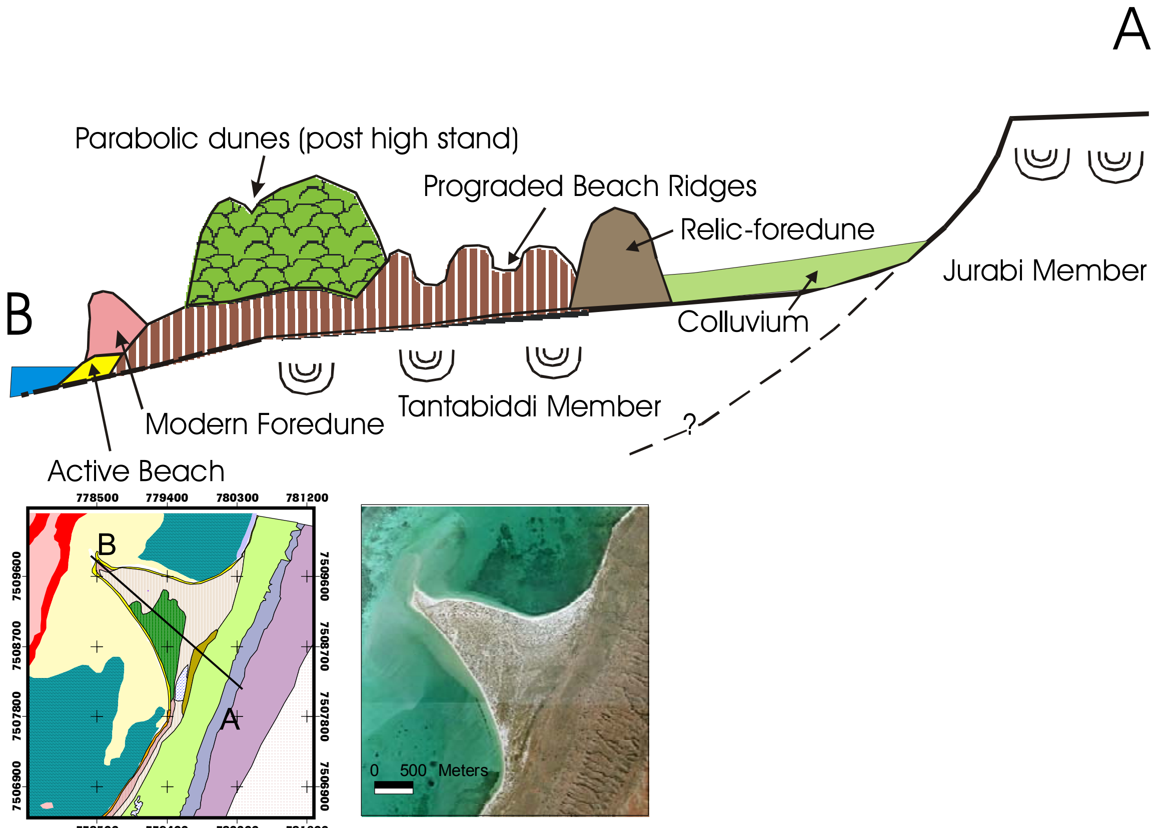


Figure 7-3. Schematic cross-section of Winderabandi Point (area A) (grid ref. 779 560,7509 103). Note the parabolic dunes prograded over the beach ridge unit. Not to scale.

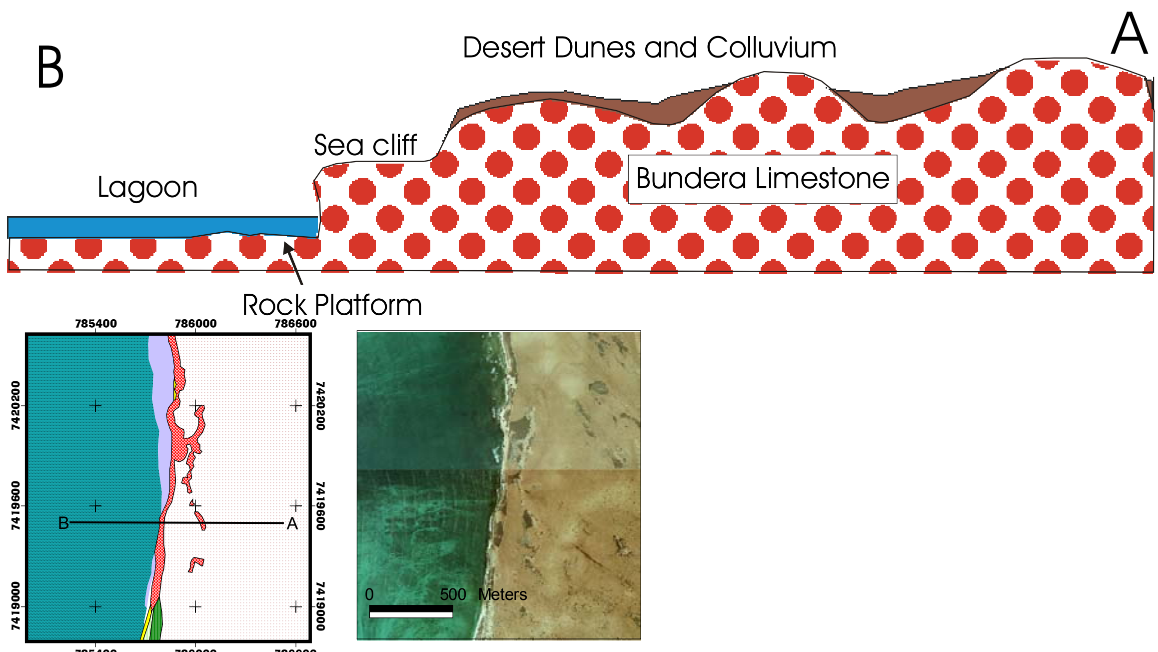


Figure 7-4. Schematic cross-section of a typical cliffed coast. This example is from area D (grid ref. 785 970, 7419 554). Not to scale.

During this highstand the marine embayments present in this area were populated by mangroves (Kendrick, 1990). The “salt lake” to the east of Coral Bay shows clear evidence of mangrove development primarily, in the form of mangrove associated molluscs, such as *Saccostrea sp. cf. S. commercialis*, found in aboriginal bidden sites. The decline in the mangrove populations has been attributed to the barring of the embayment by coastal progradation, reinforced by the Late Holocene regression stranding the mangrove community (Kendrick, 1990).

7.2.4 Holocene Evolution Stage 3. Regressive Deposits

Sealevel decreased from the end of the Late Holocene highstand to present. During this 5300 year period, the dominant deposition was the formation of beach ridge plains. As shown in Figure 3-6 and Figure 7-5, the regressive phase of coastal development is a prograding sequence from a relic-shoreline (which is frequently cliffed) or from the seaward edge of a parabolic dune field. The width of the regressive phase of coastal development varies considerably, from 500 m to 10 m wide dune plains, with wide plains developed in paleo-embayments. A number of modern parabolic dunes have developed in the four mapped areas. These are younger than the bulk of the parabolic dunes along the coast. This last stage of dune development occurred when sealevel had fallen to current levels. These dunes form when vegetation is degraded and strong oblique onshore winds mobilise older parabolic dunes and Holocene coastal sediments. These dunes can be distinguished from the older dunes as they have not been stained red from iron oxide rich dust, and are composed of clean white calcareous sand.

7.2.5 Holocene Evolution Stage 5. Modern Beach and Foredune Development

Modern foredune and beach deposits are a consequence of the active sedimentary system along the Ningaloo Coast. Lagoonal currents are predominantly responsible for this development by controlling process such as longshore drift. Active shoreface reworking and deposition exists in this zone, creating a relatively mobile system of calcareous sands. Various beach and foredune morphologies exist in the study areas and these are modified by seasonal changes.

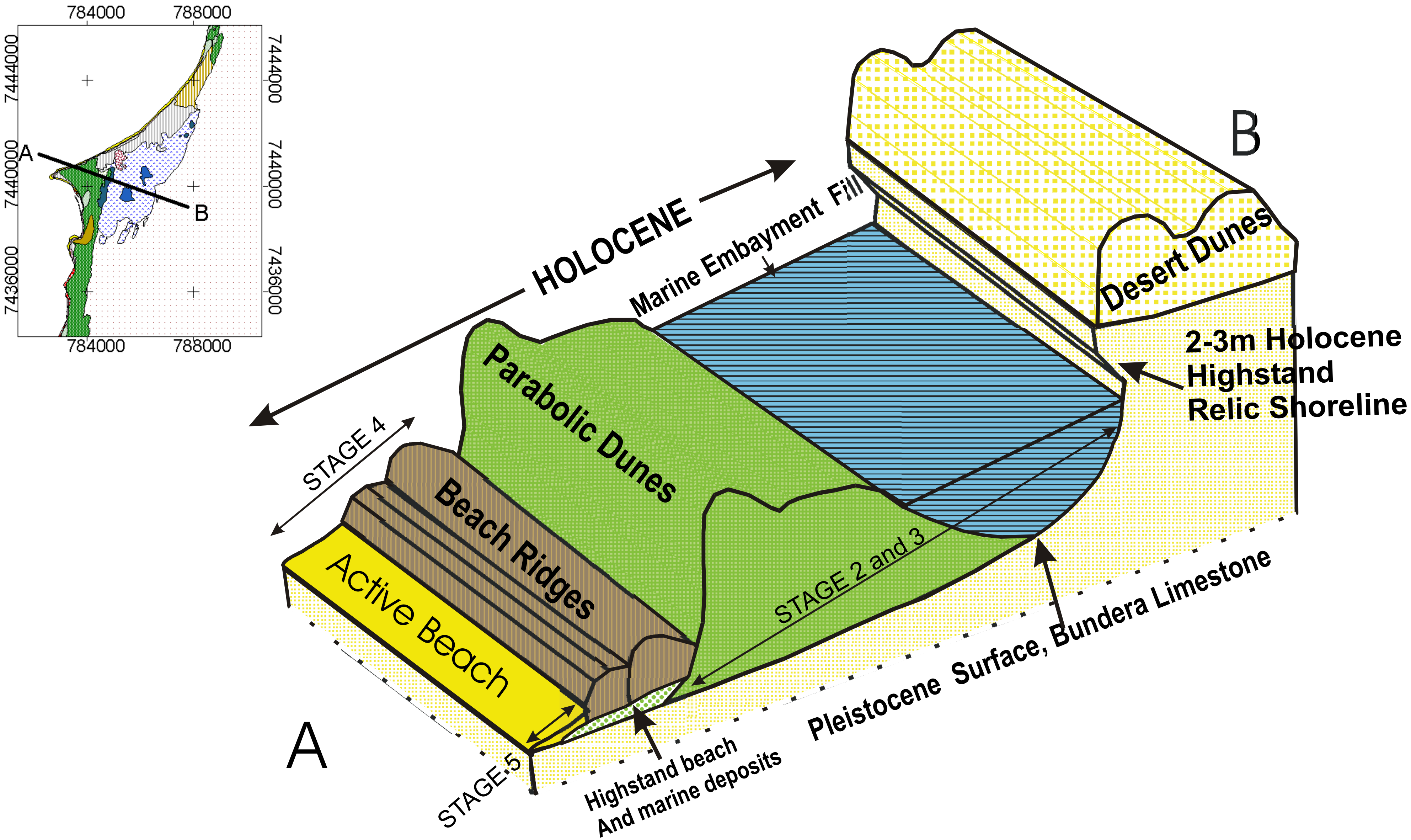


Figure 7-5. Cross-section of the major coastal units present adjacent to the Ningaloo Reef. This example is based on a section across area C (Coral Bay) but typifies prograded coastal stratigraphy in much of the four areas.

7.3 Coastal Morphological Types

The coastal segments studied in the four mapped areas are composed of combinations of four end-member coastal morphologies. Only a few examples exist of one end-member morphological type as the natural processes acting on this coast have created a complex system of morphologies, therefore whilst these four basic coastal morphologies represent the main morphological types mixed types are also present.

7.3.1 Cliffed Coast

Cliffed coast typically develops landward of a reef pass, on straight initial topography, due to the wave energy being dissipated on the coast rather that the reef crest. Sediment transport is therefore alongshore and erosion or little deposition takes place. Sea cliffs and rock platforms are commonly developed. The stretch of cliffed coast adjacent to the Yalobia Passage approximately 3 km south of Coral Bay in area C (grid ref. 784 080, 7431 780) is an example of this type of coast. Figure 7-4 is a cross section of a typical cliffed coast; it emphasises the lack of Holocene sediment deposition in this situation.

7.3.2 Embayment Fill and Beach Ridge Coast

The Holocene transgression drowned low lying embayments and deposited embayment fill. This fill continued through the highstand stage. Beach ridge plains then developed as a result of Late Holocene sealevel regression after marine deposits unfilled the marine embayments. The initial coastal topography is an embayed coast and the sediment transport is initially into the embayment then prograding out to the modern shoreline. An example of this type of coast is the beach ridge plain in area A that abuts relic-foredunes (grid ref. 774 980, 7503 990). The characteristic

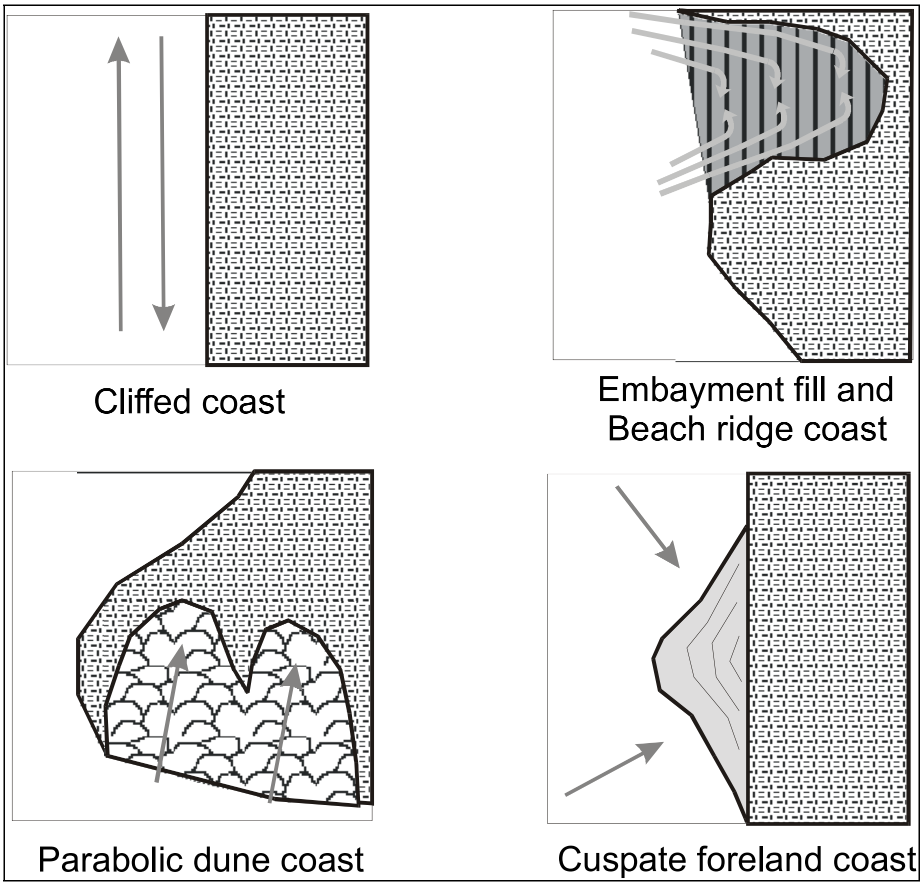


Figure 7-6. The four end-member coastal morpholgies adjacent to the Southern Ningaloo Reef.

The hatched area represents pre Holocene coastal topography, and the arrows represent the direction of sediment movement during Holocene deposition.

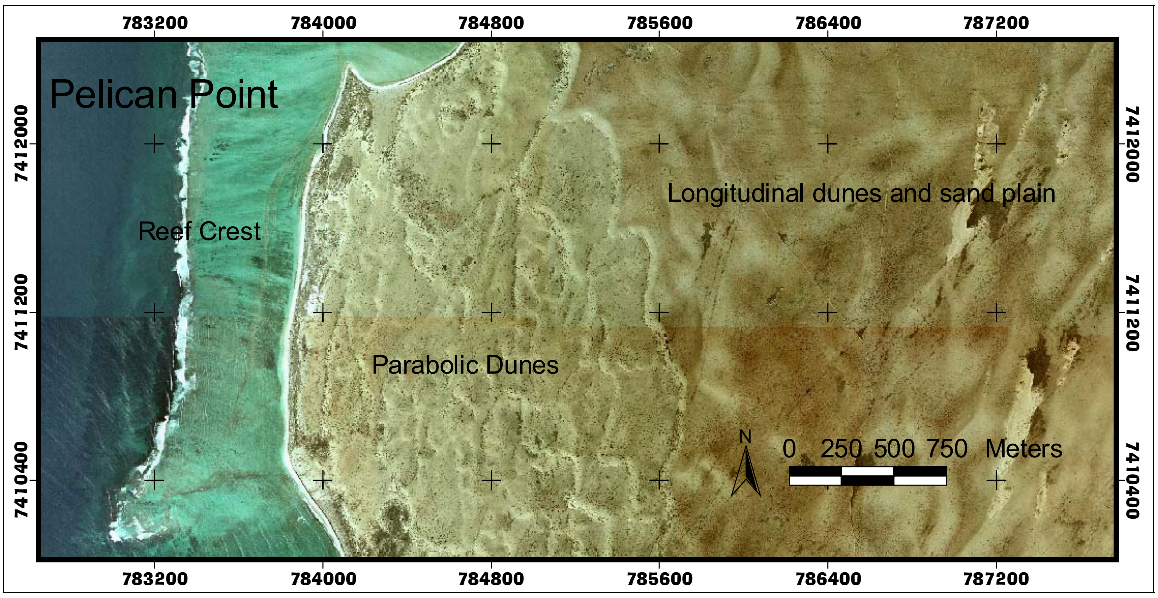


Figure 7-7. An example of a large parabolic dune field adjacent to Pelican Point in area D. Note the south aspect to the coast in the bottom of the figure.

stratigraphy is a transgressive-regressive sequence that commonly preserves stranded marine embayments as “salt lakes”.

7.3.3 Parabolic Dune Coast

A parabolic dune coast develops where the initial topography is low enough in elevation to allow sand dunes, driven landward in front of the advancing transgression, to overwhelm and bury the pre-existing coast, resulting in landward progradation of parabolic dunes. There is a correlation between coastal orientation and the size of the adjacent parabolic dune field. As a result, coasts with a more south facing aspect (as apposed to a west facing aspect) develop the widest parabolic dune fields. The driving force behind sedimentation for this coastal morphology is the persistent southerly wind that must have been present during all of the Holocene. Sediment transport during deposition was mainly from the south. These dunes have been rubified in colour by iron oxide rich dust from the inland dune fields. The parabolic due field in the south of area A is an example of a southward facing coast generating a large parabolic dune field (grid ref. 774 550, 7500680). Figure 7-5 is a schematic cross section, illustrating the stratigraphic position of parabolic dunes overlying the Pleistocene surface.

7.3.4 Cuspate Foreland Coast

Cuspate forelands develop because of passes in the reef focusing wave refraction, forming a node of sedimentation along the initial coastal topography. The shape of the initial topography is not a major controlling factor in the deposition of these features. Winderabandi Point in area A is a cuspate foreland that has been modified by the progradation of parabolic dunes over its southern edge. Another cuspate foreland exists in area D (grid ref. 785 470, 7418 010). Figure 3-6 illustrates the wave refraction patterns responsible for the development of this cuspate foreland.

Figure 7-3 is a schematic cross section of Winderabandi Point that highlights the limestone basement and prograded parabolic dunes on the cuspate foreland.

8 SUBSTRATE CAPABILITY AND IT'S SPATIAL EXPRESSION

The term substrate capability and the substrate capability index (SCI) were developed to add value to the land system unit descriptions, making them more useful for land management purposes. Substrate capability is defined as;

"The capacity of a land unit's substrate to withstand environmental impacts from natural processes and/or land use activities".

The land system unit characteristics used to determine substrate capability include unit thickness, stratigraphy, vegetation cover, topography, slope stability, constituents and consolidation, see 1.2.4 for a detailed description.

This section is designed to be read in conjunction with the supplied maps A-D, specifically the land management maps that delineate SCI and risk zones (see 8.1) for each area.

Land system units with a very low substrate capability (SCI 1) are unconsolidated, commonly active units, predominantly with no vegetation cover over steep slopes and undulating topography (see Table 6- and Table 8-1). These characteristics make the units prone to erosion and remobilisation of sediment, leading to the development of "blowouts" and large denuded areas. Land system units such as the active beach and supratidal flats are often heavily utilised by tourists, increasing the risk of significant degradation. The spatial extent of land system units with a very low substrate capability is typically narrow strips constituting active beach units (see map A grid ref 779 000, 7508 000) and larger isolated areas associated with active parabolic dunes and saline lakes/flats (see map A grid ref 775 000, 750 000).

Table 8-1. Land system units substrate capability index.

SCI	Land System Units
1 Very Low	Active beach, Modern foredune, Beach ridge plain (un vegetated), Perennial Lake, Sand Plain Blow out, Parabolic Dune (active), Saline Lake/flat, Supra-tidal Flat.
2 Low	Active beach (rocky), Beach ridge plain, Beach ridge (hummocky), Cuspate foreland, Parabolic dunes, Emergent beach, Relic-inlet spits, Relic supra-tidal flat.
3 Medium	Aeolian ridge, Deflation basin, Relic-foredune, Ground water seep, Longitudinal dunes and sand plain.
4 High	Tantabiddi aeolian ridge, Tantabiddi Terrace.
5 Very High	Bundera Limestone outcrop, Jurabi Member, Exmouth Sandstone.

Land system units with a low substrate capability (SCI 2) are predominately unconsolidated, low gradient undulating dune plains with a sparse cover of vegetation (see Table 6- and Table 8-1). The low dune slopes and minor vegetation make these units less susceptible to natural and anthropogenic impacts than units with an SCI of 1. Units classed with a SCI of 2 have a large spatial extent in areas A and C where the Holocene coast has developed to a significant width; areas B and D have relatively narrow Holocene deposition, therefore small spatial extent of SCI 2 units. Beach ridge plains constitute the largest area of SCI 2 units. These units are commonly the location of nodes of activity such as major access points or concentrated camping sites, due to their proximity to the coast, their large areal extent and relatively flat topography. This high land use commonly results in substantial areas of degraded dunes caused by uncontrolled networks of tracks, examples include; the beach ridge plain to the south of Point Billie (area A grid ref. 775 000, 7504 000 and Figure 8-1) and the beach ridge plain in the north of the Pelican point area (area D grid ref. 785 000, 7423 000).

The land system units classed as having a medium substrate capability (SCI 3) are either medium to well vegetated, unconsolidated sandy units such as deflation basins and relic-foredunes, or longitudinal dune and sand plains characterised by a thin cover of colluvium over heavily calcretised limestone (see Table 6- and

Table 8-1). The longitudinal dune and sand plain unit backs all mapped areas to the east, constituting over half of all mapped land area; the spatial extent of SCI 3 units is therefore very large. The only instances of significant degradation in these units are small "blowouts" of red colluvial sands in the longitudinal dunes and sand plain, in areas of thick colluvial cover intersected by access tracks or areas of stock or fire damage.

The Tantabiddi terrace unit and associated aeolian ridge constitute the units with a high substrate capability (see Table 6- and

Table 8-1). The Tantabiddi terrace is a predominantly flat limestone plain with a 0-3 m cover of unconsolidated soils and calcareous sands on the flat topography. The flat topography and thin unconsolidated cover over a limestone base make the unit relatively unsusceptible to "blow outs" or other disturbance. No significant degradation was observed on this unit during fieldwork.

The units classified as having a very high substrate capability (SCI 5) are all Pleistocene limestones with a very thin to non-existent cover of colluvial material. These units typically outcrop as small isolated domes or platforms either on a topographic high or as cliffed coastal exposure. The only widespread outcrop is the foothill of the Cape Range in the Winderabandi Point area (area A). The level of degradation possible on these units in negligible due to their consolidated state, however the isolated nature of these units makes them relatively insignificant in terms of land management.

8.1 Risk Zones

In order to highlight problem zones in the four mapped areas (Winderabandi Point, Brooboodju Point, Coral Bay and Pelican Point) a systematic method of delineating risk zones was developed. A risk zone is an area of land that is currently highly utilised for track access and but has a low substrate capability and therefore is currently at risk of substantial degradation. Risk zones were identified as areas of land with a very low to low substrate capability (SCI = 1 or 2) and high land use; (greater than 280 m of track in four hectares), see section 1.2.6 for the full description of the method used to delineated these zones. Maps A-D include a land management map that presents all the risk zones identified in the four mapped areas. A quantitative assessment of the area of each land system unit affected by risk zones was completed, (Figure 8-3 to Figure 8-6) allowing for an assessment of the fragile land system units under the most pressure from anthropogenic impacts in each mapped area.

In the Winderabandi Point area the beach ridge units constitute the majority (146 acres) of land system units classified as at risk. The majority of this beach ridge risk area is due to the popular camping area to the south of Point Billie (grid ref. 7504 000, 775 000). Major problems have developed in this area due to uncontrolled track development, see Figure 8-1 and map A.

Risk zones in the Brooboodju Point area (area B) are dominated by the very popular camping area at Brooboodju Point. The sites are situated on a supra-tidal flat adjacent to the modern foredune, see Figure 8-4. Up to 20 separate site occupy the supra-tidal flat and 3 sites have been developed in the parabolic dunes in the south, see Figure 8-2 and map B.

The majority of the risk zones delineated in the Coral Bay area (area C) are associated with the heavy access use of the Coral Bay “salt lake”. The network of tracks on this saline flat unit has resulted in 476 acres of saline flat defined as a risk zone, see Figure 8-5. Parabolic dunes being utilised for beach access has resulted in

274 acres of this unit delineated as a risk zone, see Figure 8-5. Many of these access tracks are particularly steep and unstable, causing significant local degradation and map C (see Figure 5-2).

The Pelican Point area has a relatively small area of risk zones that are predominantly located on parabolic dunes (68 acres) and beach ridges (42 acres) see Figure 8-6. A camping area referred to as “Steve’s” (grid ref. 784 000, 7403 500) is the most utilised area in the Pelican Point area (area D). This camping area includes substantial track development on a beach ridge plain and modern foredune causing the initiation of dune degradation, see map D.

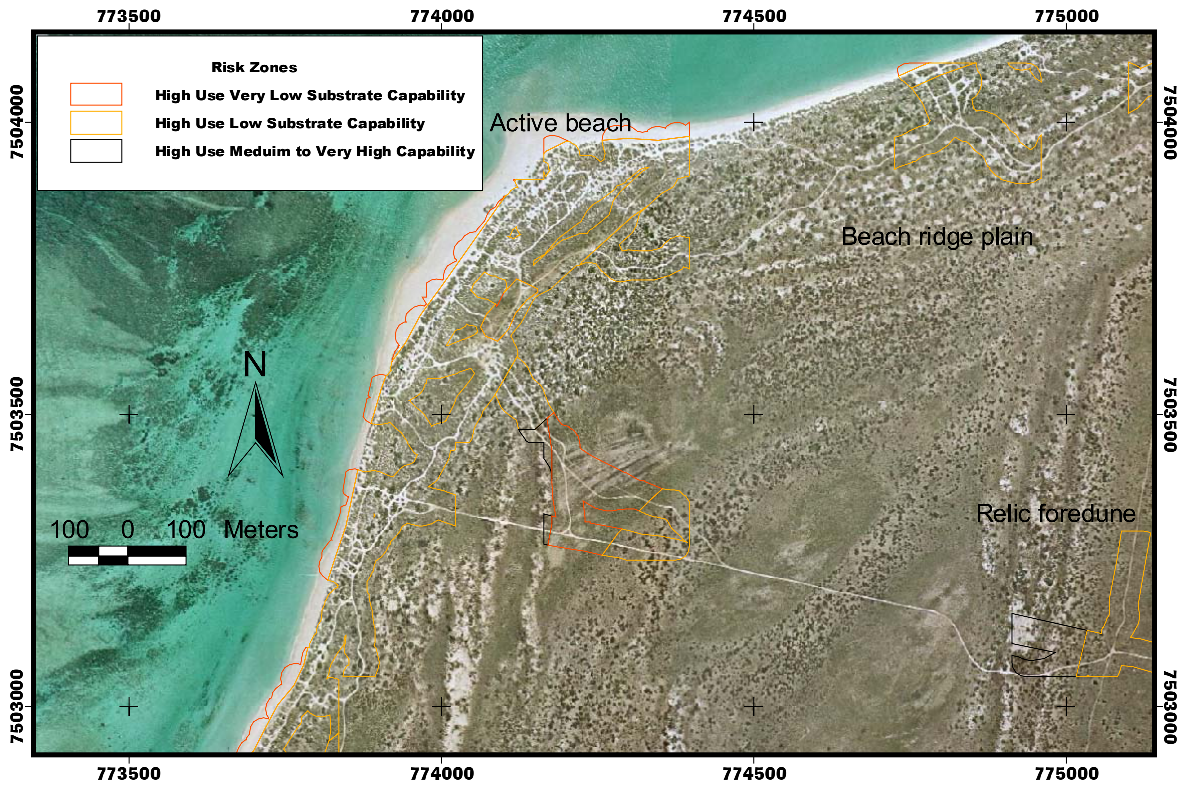


Figure 8-1. The popular camping area south of Point Billie in area A. Risk zones are overlayed on air photo, note the advantage of the risk zone delineation sytem that incorporates active beach zones at risk from heavy access through landward units.

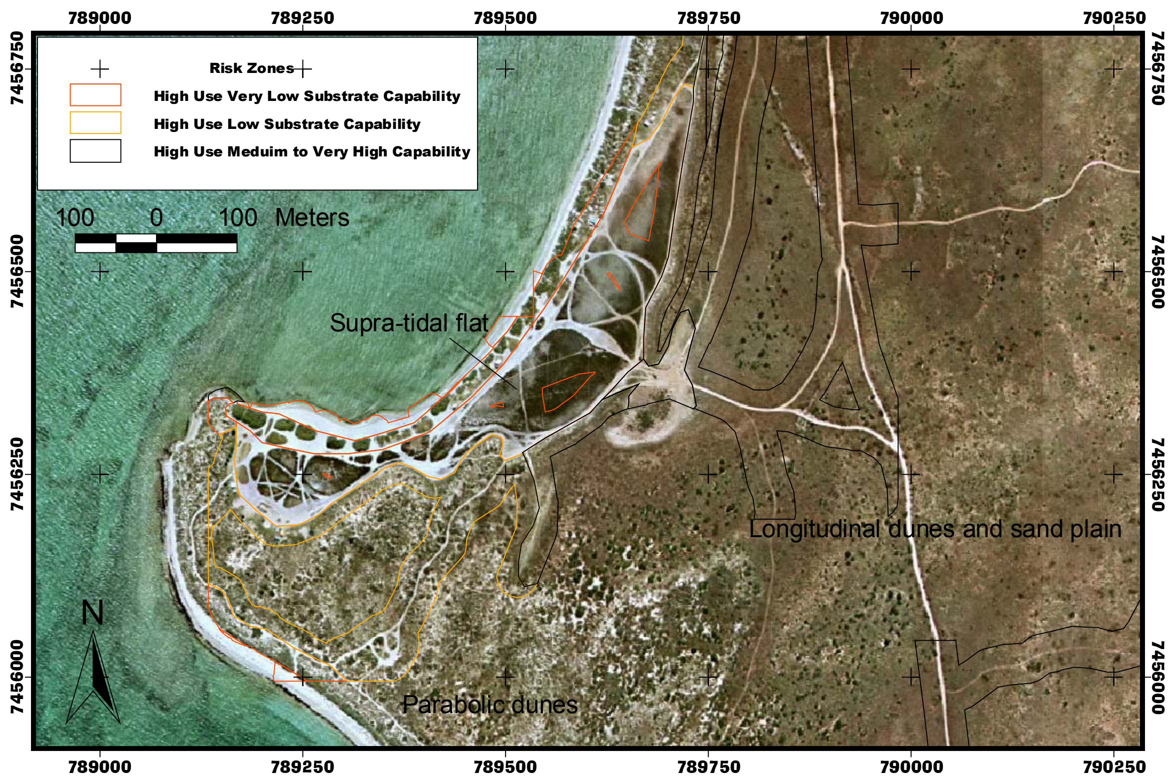


Figure 8-2. The popular camping area at Brooboodju Point with overlay of risk zones.

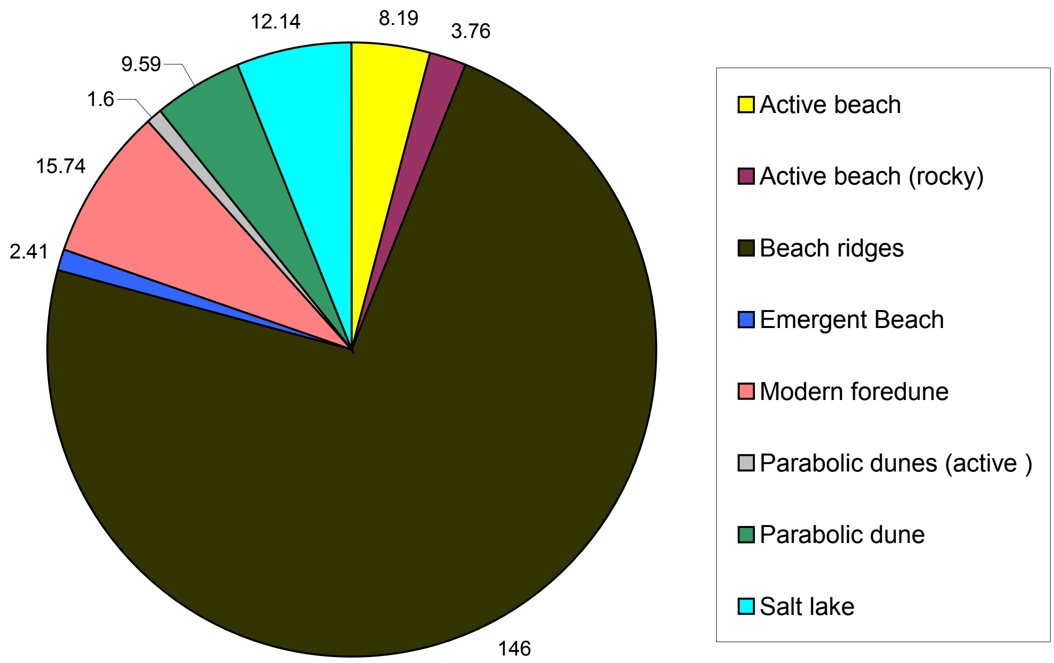


Figure 8-3. The areal extent of risk zones in the Winderabandi Point area (area A).

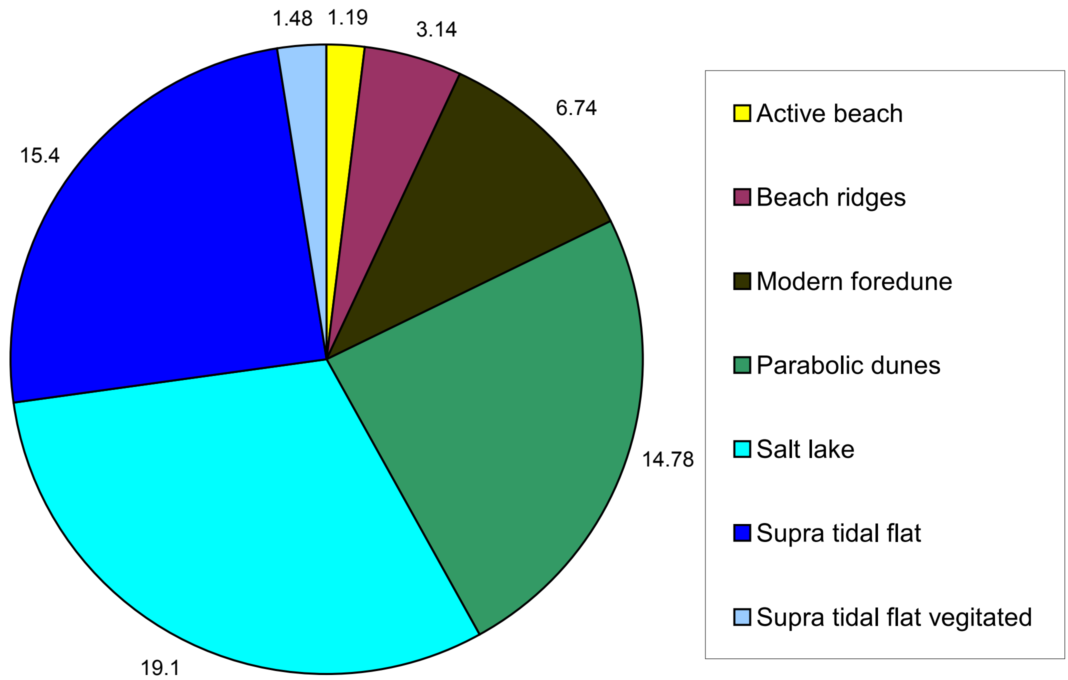


Figure 8-4. The areal extent of risk zones in the Brooboodju Point area (area B).

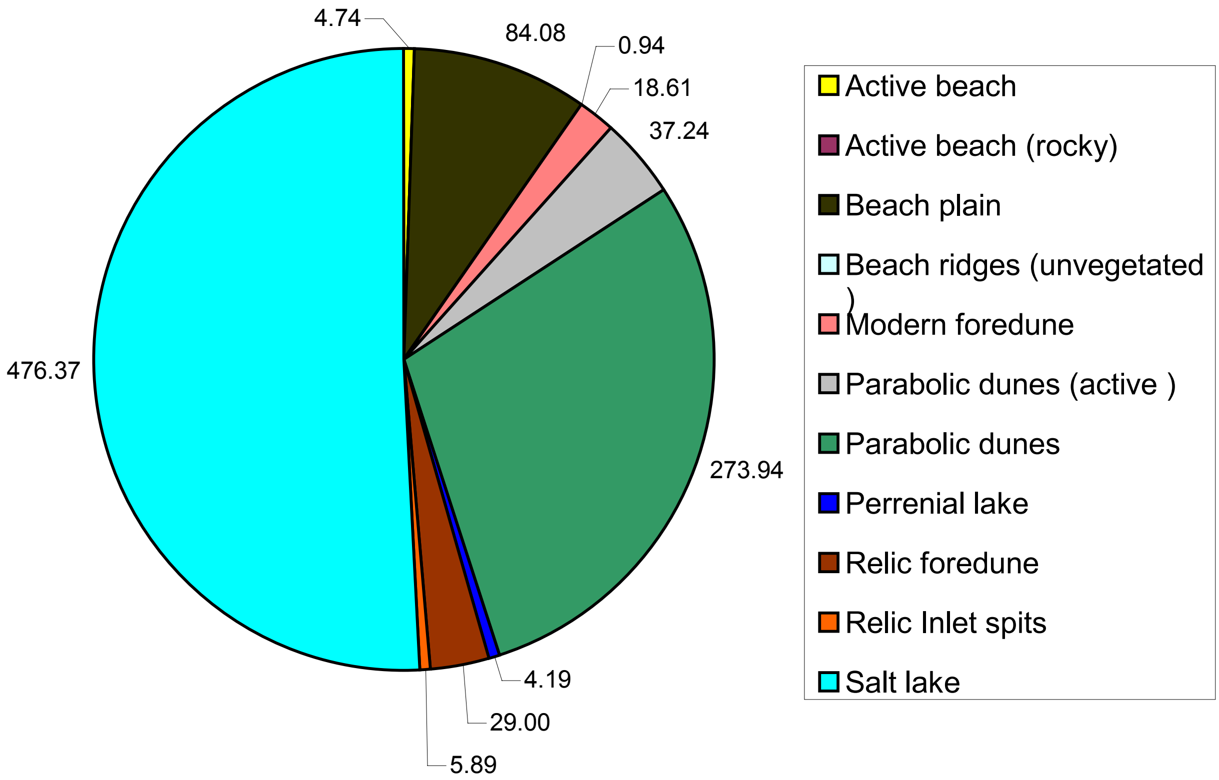


Figure 8-5. The areal extent of risk zones in the Coral Bay area (area C).

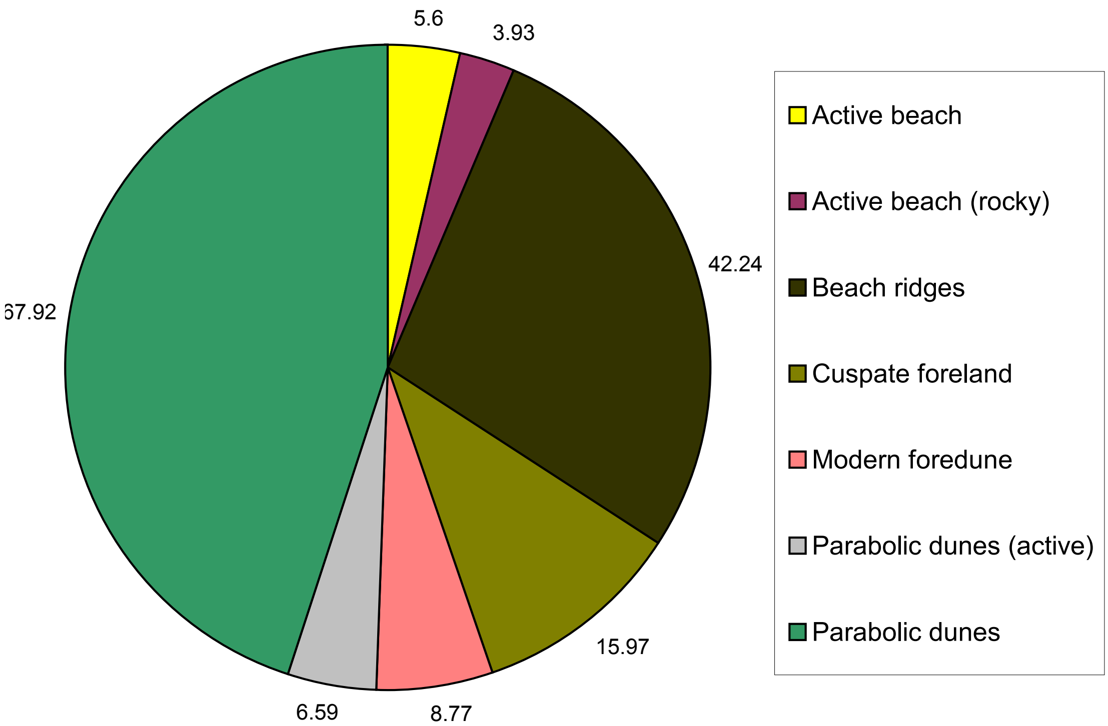


Figure 8-6. The areal extent of risk zones in the Pelican Point area (area D).

9 CONCLUSIONS

The coastal zone adjacent to the Ningaloo Reef is composed of a Pleistocene limestone hinterland and a narrow Holocene sandy fringe. The morphology and structure of Quaternary coastal evolution have been controlled by physical processes that continue to operate and modify this coastal system. The dominant physical processes responsible for the evoluton and modification of this coast are; present and past climate, oceanography and sealevel variations.

The initial topography of the Pleistocene Bundera Limestone provides the pre Holocene surface and creates nodes of sedimentation associated with limestone headlands. The Quaternary development of the Ningaloo Reef has, however, controlled local currents and associated sedimentation, by the development of circular flow patterns in the lagoon, providing varying amounts of coastal protection and refracting waves which control sediment transport.

A distinctive stratigraphy has developed along this coast as a reflection of Late Holocene transgression, highstand and regression. Large parabolic dune fields were deposited during transgression and highstand. A series of relic coastal features such as marine embayments and shorelines were generated by erosion and deposition during the highstand. Beach ridge plains then formed due to of regression as sediment fills over the drowned embayments.

All mapped areas are contained within dune and cuspate spit coast, characterised by the presence of the barrier reef offshore and cuspate forelands and beach ridges onshore. The Winderabandi Point area (area A) is characterised by a limestone hinterland, including terraced Cape Range foothills, adjacent to a sandy cuspate foreland in the north, a central rocky bay, a relic coastal sequence of linear dunes and a large parabolic dune field and in the south. The Brooboodju Point area (area B) is characterised by an undulating limestone hinterland with a thin colluvial cover, a narrow coastal strip of Holocene dunes and a limestone headland with associated supra-tidal flat. The Coral Bay area (area C) is characterised by substantial coastal limestone outcrop and a narrow Holocene coastal fringe in the north, a large stranded marine embayment, beach ridge plain and composite spit in the cental part, and embayment fill, linear dune plains and cliffed coast in the south. The Pelican Point area (area D) is characterised by an undulating limestone hinterland with a thin colluvial cover and a predominantly narrow coastal strip of Holocene dunes, but includes a wide parabolic dune field associated with a limestone headland and two linear dune plains.

The four mapped areas in this report were chosen as they are high land use zones, and the level of anthropogenic impacts reflects this. Access track development has the greatest impact as it is frequently uncontrolled, causing the proliferation of networks of tracks. Significant degradation of this fragile environment, predominantly erosion and remobilisation of sediment, occurs despite land and tourist management strategies put in place by respective Stations. Degradation is associated with nodes of activity that are typically established camping sites, heavily used access tracks or camping facilities.

Land system units with low substrate capability are unconsolidated, commonly mobile units, predominantly with little to no vegetation cover over steep slopes and undulating topography, making them prone to erosion and remobilisation of sediment. Land system units such as the active beach and supratidal flats are often heavily utilised by tourists, increasing the risk of significant degradation.

Land system units with a medium to high substrate capability consist of consolidated limestone with a thin to non-existent cover of colluvial material and significant vegetation cover. The level of degradation possible on these units is reduced due to the increased erosion resistance afforded by the vegetation cover and consolidated substrate.

The delineation of risk zones, based on GIS analysis of track density and substrate capability, identified areas of land particularly at risk of degradation due to a combination of substrate characteristics and level of land use. The information produced in this study is useful for land management purposes as it quantifies the impacts on the coastal zone and allows for the development of more effective strategies for management. A major review of land management practices in the region is currently being undertaken by government agencies, and the local and regional environmental data produced in this study will be of direct assistance to this process.

10 RECOMMENDATIONS

- Continued coastal mapping should be accomplished in order to complete the stretch of coast adjacent to Ningaloo Reef as part of the continued effort to develop the spatial database currently being expanded by CALM.
- The production of a high precision Holocene sealevel history for this coast should be developed, through a detailed study of coastal stratigraphy involving a significant drilling and corresponding dating program.
- A study of the specific impacts related to the risk zones delineated in this study should be undertaken, with the aim of improving management of these fragile areas in close proximity to the Ningaloo Reef.
- Detailed documentation of plant communities existing on the hinterland adjacent to the Ningaloo Reef, due to the importance of vegetation variations on the stability of the coastal system.
- The completion of a recreation and tourism study in the region to further quantify impacts and opportunities in the area.
- Land managers need to view the Ningaloo Coast as an interactive system, incorporating the oceanic, lagoonal, coastal and hinterland zones. In addition, the region must be managed with the same approach.

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Appendix

1. Reasoning for the 28-point cut off and 25m buffers used in the delineation of risk zones.

In order to separate high land use zones from low to medium zones a cut off point of 280m of track in a 4-hectare square was used (See 3.2 GIS for the description of the process). The 280m (28 point) cut off was devised from both quantitative and qualitative methods.

Once an overlaying grid had been attributed with track density, in the form of point counts, a histogram was produced of the number points in a cell, see charts 1-4 (the line is the 28 point cut off). This line was deemed the best divide between average land use and high land use.

This initial judgment was then checked by a visual assessment of the coverage of the cells with a point count greater than 28 over known high use zones. After applying these two methods, the cut off of 280m of track per four hectares was deemed appropriate as a consistent way of delineating high use zones.

A buffer of 25m was applied to both the high land use cells and the access tracks during the delineation of high land use zones (see 3.2 GIS for an explanation of method). 25 m is an estimate of the area of land adjacent to an access track that has the potential to be affected by that track in the near future.

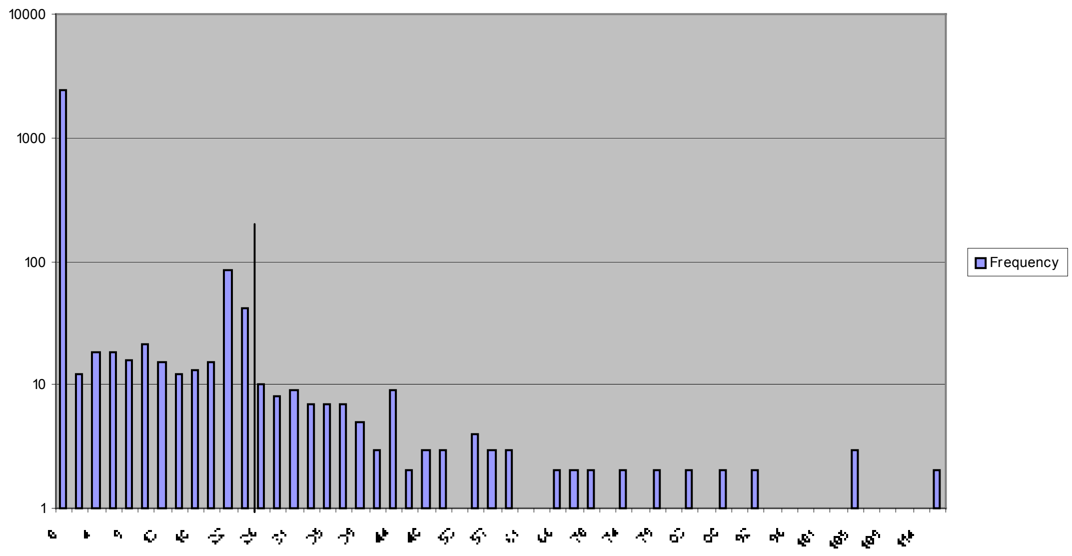


Chart 1 Histogram of access point counts in 4-hectare cells for Area A (Winderabandi Point)

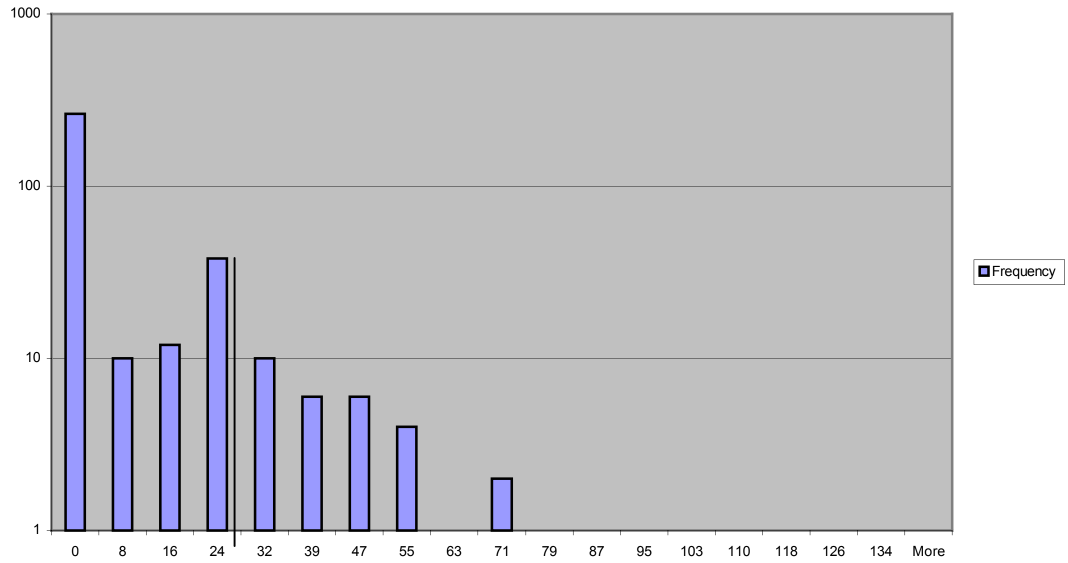


Chart 2 Histogram of access point counts in 4-hectare cells for Area B (Brooboodju Point)

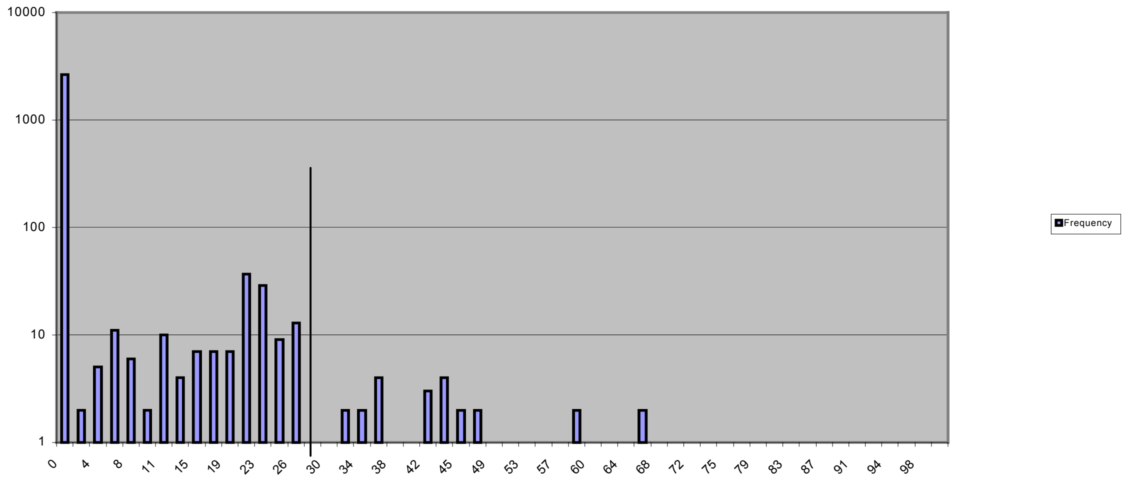


Chart 3 Histogram of access point counts in 4-hectare cells for Area C (Coral Bay)

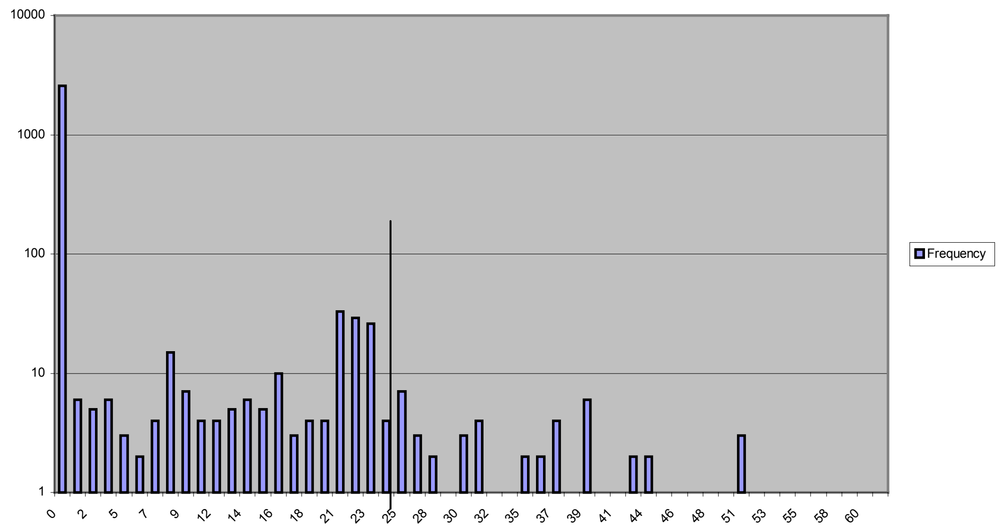
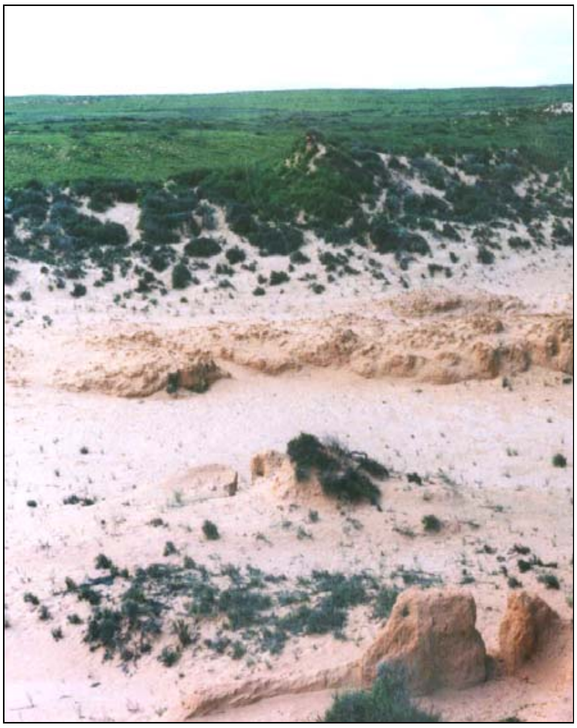


Chart 4 Histogram of access point counts in 4-hectare cells for Area D (Pelican Point)

2. Petrographic Descriptions.

Specimen Number S31Dc

Location Description	Blow out in parabolic dune exposing core.
Colour……………..	Red
Unit…………………	Parabolic dune
Structure…………..	1-2 cm cross beds
Approximate age….	Early Holocene
Grain size…………	Fine to Medium sand
Sorting…………….	Good
Rounding…………	Good
Porosity……………	High ≈20%
Topography………	Rounded parabolic dune with curved prograding faces. Up to 40m high.
Stratigraphy………	Overlies Bundera Limestone.



Exposed core of parabolic dune north of Pelican Point area D.

Constituents	Comments	% Total
Calcareous algae		20
Molluscs	Including gastropods	15
Lithoclasts	Contains high amounts of micrite.	15
Echinoid		10
Bryozoans		10
Quartz	Trace	5
Forams		2
K feldspar	Trace	1

Interpretation

Unlithified skeletal grain stone. Comprised of open marine assemblage.

Partly lithified core parabolic dune. Exposed by blow out.

Remarks

Blow out probably caused by vegetation loss due to fire.

Figure 6-1 E for thin section image.

Specimen Number S28Da

Location Description	Intertidal bedded outcrop.
Colour……………..	Cream (red speckled)
Unit…………………	Bundera Limestone outcrop
Structure…………..	10-20 cm beds at low angle.
Approximate age….	Pleistocene
Grain size…………	Medium to coarse sand
Sorting…………….	Poor
Rounding…………	Good
Porosity……………	High ≈15%
Topography………	Bedded intertidal beach outcrop.

Aerial view of outcrop 11 km north of Pelican Point, area D. Top to bottom = 600m.

Stratigraphy………	Overlain by sandy beach deposits.

Constituents	Comments	% Total
Coralline Algae		25
Molluscs		25
Forams		10
Echinoid spines		10
Coral		10
Bryozoans		5
Quartz		5
Cement	Fibrous incipient aragonite.	5

Interpretation

Lithified skeletal Grain stone (Beach rock).

Remarks

Specimen Number S34Dl

Location Description	Intertidal outcrop forming point.
Colour……………..	Cream
Unit…………………	Bundera Limestone outcrop
Structure…………..	30 cm flat blocky beds heavily disturbed.
Approximate age….	Pleistocene
Grain size…………	Medium to coarse sand
Sorting…………….	Poor
Rounding…………	Good
Porosity……………	High≈15%
Topography………	Low lying intertidal beach outcrop.

The view from Pelican Point looking north showing limestone coast and rubble from Tropical Cyclones.

Stratigraphy……… Overlain by sandy beach deposits.

Constituents	Comments	% Total
Coralline Algae		30
Molluscs		20
Forams		10
Echinoid spines		10
Lithoclasts		10
Bryozoans		5
Quartz		5
Cement	Fibrous incipient aragonite.	5

Interpretation

Lithified skeletal grainstone (beach rock) deposited in the intertidal zone.

Remarks

Very high density.

See Figure 6-1 F for thin section image.

Specimen Number S40ae

Location Description	Intertidal outcrop in Lefroy Bay.
Colour……………..	White
Unit…………………	Tantabiddi Member.
Structure…………..	30 cm laminated bed overlain by coarse-grained limestone.
Approximate age….	Last Interglacial. 125000 Bp
Grain size…………	Fine
Sorting…………….	Very good
Rounding…………	Medium
Porosity……………	Very high ≈30%
Topography………	Rock coastline including low cliffs and rock pavements.


Outcrop of laminated algal mat at Lefroy Bay area A. (Pen for scale).

Stratigraphy……… Overlain by modern dune deposits and active beach.

Constituents	Comments	% Total
Calcareous algae	Laminated algae with minor infill of terrigenous and skeletal material.	60
Quartz	Trace	4
Bryozoan	Trace	3
Mollusc	Trace	3

Interpretation

Calcareous algae deposit formed in supratidal conditions. Sealevel subsequently rose and deposited the overlying sandy limestone.

Remarks

Very friable.

Specimen Number S33Df

Location Description	Dune crest of calcretised Bundera.
Colour……………..	Cream
Unit…………………	Bundera
Structure…………..	Cross bedded and tabular planar bedding.
Approximate age….	Pleistocene
Grain size…………	Medium to coarse sand
Sorting…………….	Poor
Rounding…………	Poor
Porosity……………	Low
Topography………	Rounded calcretised dunes crests inland and cliffed coastal out crop.

Eolian component of Bundera Limestone in outcrop showing both cross and tabular bedding.

Stratigraphy……… Overlain by Pliocene desert dune cover, parabolic dunes, beach ridges and active beach.

Constituents	Comments	% Total
Quartz		25
Micrite		20
Calcareous Algae		10
Lithoclasts		10
Forams		5
K Feldspar		1

Interpretation

Lithified digenetic packstone stone.

Calcretised and eolian dune system.

Remarks

Has a 0-4m cover of red colluvium containing calcrete layers and nodules.

Specimen Number S26Cq

Location Description	Surface of active parabolic dune.
Colour……………..	White
Unit…………………	Active Parabolic dune
Structure…………..	
Approximate age….	Holocene
Grain size…………	Fine to medium sand
Sorting…………….	Poor
Rounding…………	Good
Porosity……………	High ≈20%
Topography………	Barren/mobile parabolic dune.

The prograding face of the large active parabolic dune north of Bills Bay.

Stratigraphy……… Overlies Bundera Limestone and stationary parabolic dunes.

Constituents	Comments	% Total
Calcareous algae		55
Molluscs		20
Quartz		10
Bryozoans		5
Lithoclasts		5
Forams	Including Miliolid and Peneroplid, (open marine assemblage.)	5

Interpretation

Unlithified skeletal grain stone Composed of an open marine assemblage.

Remarks

Sample from a large mobile dune extending from the north of Bills Bay off Skeleton Beach.

Specimen Number 2bBr

Location Description	Low lying saline flat with hard substrate of calcrete.
Colour……………..	Red and cream.
Unit…………………	Bundera Limestone outcrop
Structure…………..	Calcretised.
Approximate age….	Pleistocene
Grain size………..	Medium to coarse sand
Sorting…………….	Poor
Rounding………..	Medium
Porosity……………	Low
Topography………	Swallow substrate to a saline flat.
Stratigraphy………	Overlain by saline marine deposits.

Surface outcrop showing calcretised margin.
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Constituents	Comments	% Total
Micrite		40
Skeletal grains	Obscured by micrite but includes echinoids, molluscs (gastropods) and forams.	40
Calcareous Algae		15
Quartz		5

Interpretation — Heavily calcretised marine diagenetic packstone.

Remarks

3. Instructions to view GIS data

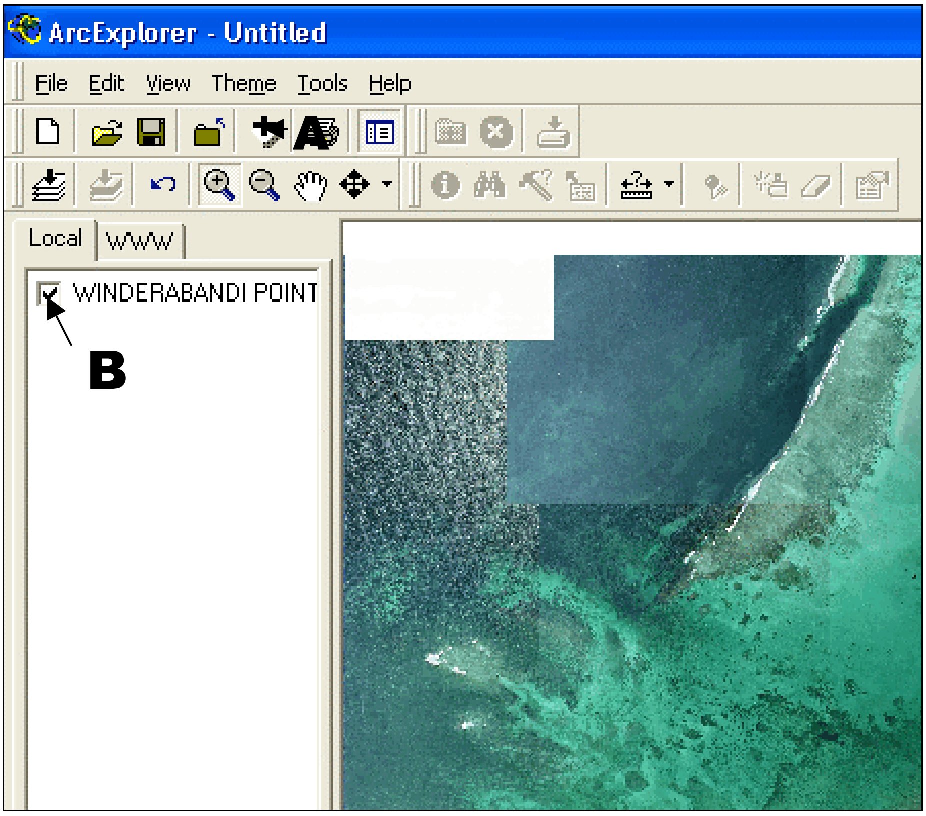
The accompanying cd rom to this dissertation is designed to allow interactive viewing of the GIS data created for the projects and supply a resource for further study in the region.

How to install Arc Explorer software and view GIS data

To install arc explorer simply run the installation program

```
diss cd\ arc explorer setup
```

To Add data to the view press the add theme botton (A)

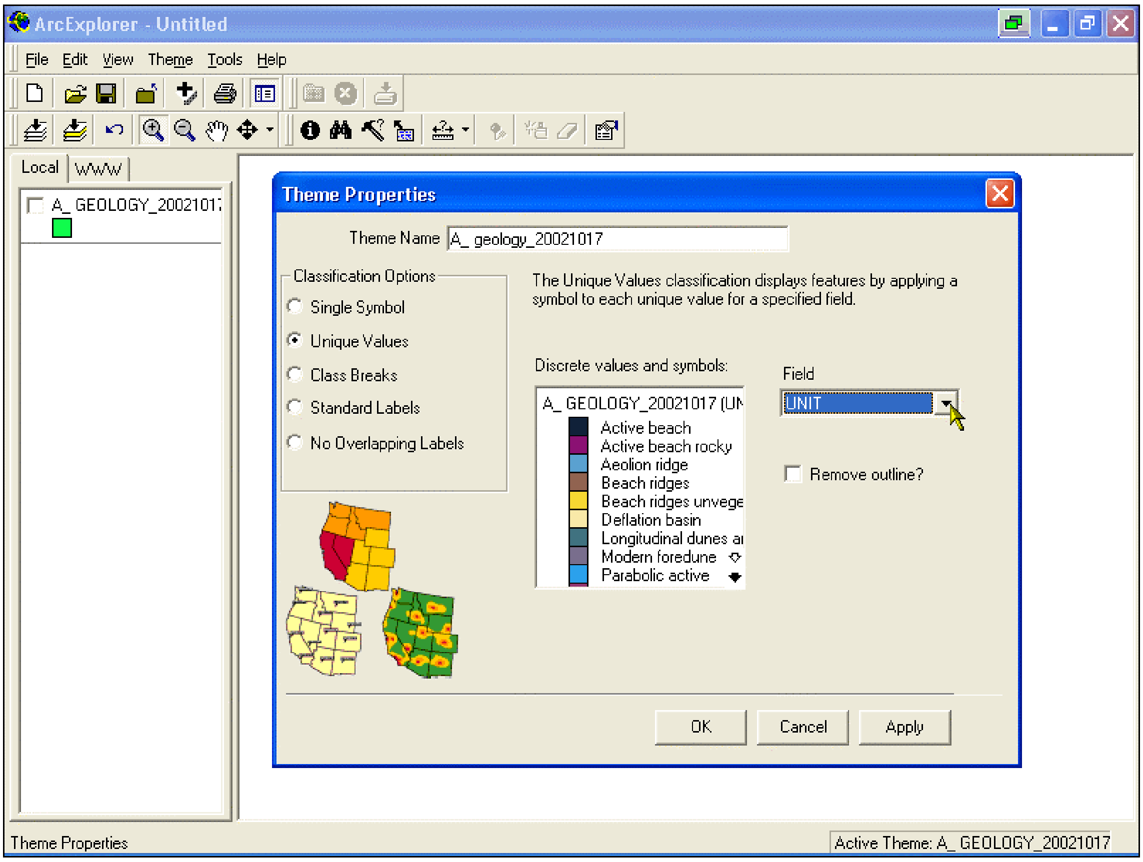


To make a theme active check the box at B.

Add all data you want to view including air photo back ground from (Diss CD\GIS data\geojpgs) but images will slow work up considerably so only keep them active when needed.

To change the display of theme double click on the theme in the item list.

The following window will appear. For all themes use "unique value" classification and choose "unit" as the field for geology, "type" for access and "capability" for risk zones.



The program has a very substantial help system.

Digital versions of the map sheets and dissertation are also provided for reference purposes as well as a selection of references used in the dissertation in .pdf format.

4. Contents of accompanying CD rom.

`Diss CD\Dissertation` (digital copy of full dissertation in pdf format)

`Diss CD\GIS data` (all raw GIS data)

`Diss CD\GIS data\Geology`

`Diss CD\GIS data\Geology\D`
`Diss CD\GIS data\Geology\C`
`Diss CD\GIS data\Geology\B`
`Diss CD\GIS data\Geology\A`

`Diss CD\GIS data\analysis`
`Diss CD\GIS data\analysis\Risk areas`

`Diss CD\GIS data\Access`
`Diss CD\GIS data\Access\D`
`Diss CD\GIS data\Access\C`
`Diss CD\GIS data\Access\B`
`Diss CD\GIS data\Access\A`

`Diss CD\GIS data\geojpgs` (reduced quality/size air photos for the four mapped areas)

`Diss CD\PDF Maps` (digital version of maps A-D)

`Diss CD\articles` (selected references in digital/pdf format)

Maps

Map	Area
A	Winderabandi Point
B	Bruboodjoo Point
C	Coral Bay
D	Pelican Point