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Quaternary coastal evolution adjacent to southern Ningaloo Reef, Western Australia: Implications for land use planning.

Bachelor of Science (Applied Geology) (Honours) 2003.

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Quaternary coastal evolution adjacent to southern Ningaloo Reef, Western Australia: implications for land use planning.

By

Cherie Louise Leeden

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

Department of Applied Geology

Abstract

The 290 km long segmented, fringing Ningaloo Reef of Western Australia lies between latitudes 21°47’ and 24°S along longitude 113°30’E. Nearshore currents, controlled by the reef, dictate both marine and terrestrial sedimentary systems and provide a modern analogue for the adjacent uplifted and preserved paleo-reefs. The present day reef records Holocene and Last Interglacial phases of reef growth in a tectonically stable environment, overlying uplifted Tertiary carbonates of the Cape Range, which is flanked by raised Plio-Pleistocene terraces and reefs.

The coastal plain adjacent to Ningaloo Reef and the Cape Range region, provides evidence of coastal evolution, tectonic uplift, global sea-level changes, coastal aeolian processes, desert aeolian processes and karstic processes. Interactions between these processes have determined the geomorphology and stratigraphy of the region. The Holocene evolution of the coastal plain adjacent to Ningaloo Reef records five depositional stages; shelf erosion and shore face retreat, transgressive deposits, highstand deposits, regressive deposits, and modern beach and foredune development. As a reflection of these influences, large parabolic dune fields were deposited during the transgression and highstand, relic coastal features generated during highstand, and beach ridge plains formed during the regression.

The regional geomorphology varies from rugged Tertiary limestone cliff coasts adjacent to the southern extent of Ningaloo Reef, to Holocene sandy active beaches on the coast adjacent to the northern extent of the reef. The pre-existing topography has largely

dictated Holocene depositional regimes. An expansive Pleistocene desert dune plain dominates the regional inland geomorphology and is indicative of past aridity. The coastal plain in mapped areas is typically characterised by a narrow coastal strip of Holocene dunes, including rocky and sandy shorelines, modern foredunes and relic foredunes, beach ridges and parabolic dune fields. However, sections of coast adjacent to the southern extent of Ningaloo Reef have no Holocene deposition where high Tertiary cliff coasts abut the waters edge.

The coast adjacent to Ningaloo Reef is rapidly increasing in popularity as a preferred tourist destination and this has led to increasing degradation of the fragile coastal environment. This degradation is primarily related to nodes of activity, in the forms of uncontrolled proliferation of access tracks and clearing vegetation for camping sites. Geomorphological mapping of the coastal zone, integrated with a land classification scheme based on substrate capacity, provides a regional data base that enables natural and anthropogenic coastal environmental impacts to be assessed. The development of a land classification scheme based on substrate capacity was incorporated with land system units (geological units, further defined by environmental characteristics) to assist in future land management and environmental monitoring. Land system units with low substrate capacity are unconsolidated, have little to no vegetation, are commonly mobile units that take form in steep slopes and undulating topography, making them prone to sediment remobilisation and hence degradation. Land system units with a medium to high substrate capacity consist of consolidated limestone with a thin to non existent cover of colluvial material and significant vegetation cover.

Based on GIS analysis, risk zones were delineated, and areas which are particularly at risk of degradation due to a combination of the level of land use and substrate characteristics were highlighted. This study is of direct benefit for land management and planning purposes as it quantifies the impacts on the coastal zone and allows for the development of more effective management strategies. It is expected that the geological, environmental and geographic information system (GIS) data produced in this study will form the platform for further research work in this area.

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1. INTRODUCTION

The Ningaloo Reef of Western Australia is a segmented fringing coral reef that stretches for approximately 290 km from Northwest Cape to Red Bluff (Figure 1-1-A), making it the longest fringing coral reef in Australia. It is the only extensive coral reef in the world that fringes the west coast of a continent; this is due to the presence of the warm, low salinity Leeuwin Current which flows down the continental shelf margin from the tropical regions north of Australia. The environmental value of this area has been recognised by the establishment of the Ningaloo Marine Park and by the recent government submission for the reef and its surroundings to be listed as a World Heritage Site. However the existing Ningaloo Marine Park does not encompass the southern extent of the Ningaloo Reef ecosystem, and this led the Marine Parks and Reserves selection working group (1994) to propose an extension of the Marine Park to Red Bluff in order to incorporate the entire Ningaloo Reef ecosystem (Figure 1-1-B).

The coast adjacent to Ningaloo Reef is situated within both the Exmouth and Gascoyne Sub-basins of the Carnarvon Basin (Hocking, 1990). 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 aeolian and marine sediments, and are an indication that the coastal margin has experienced tectonic activity during the Cenozoic (van de Graaff et al., 1980).

The Ningaloo Reef controls nearshore currents that in turn determine both marine and

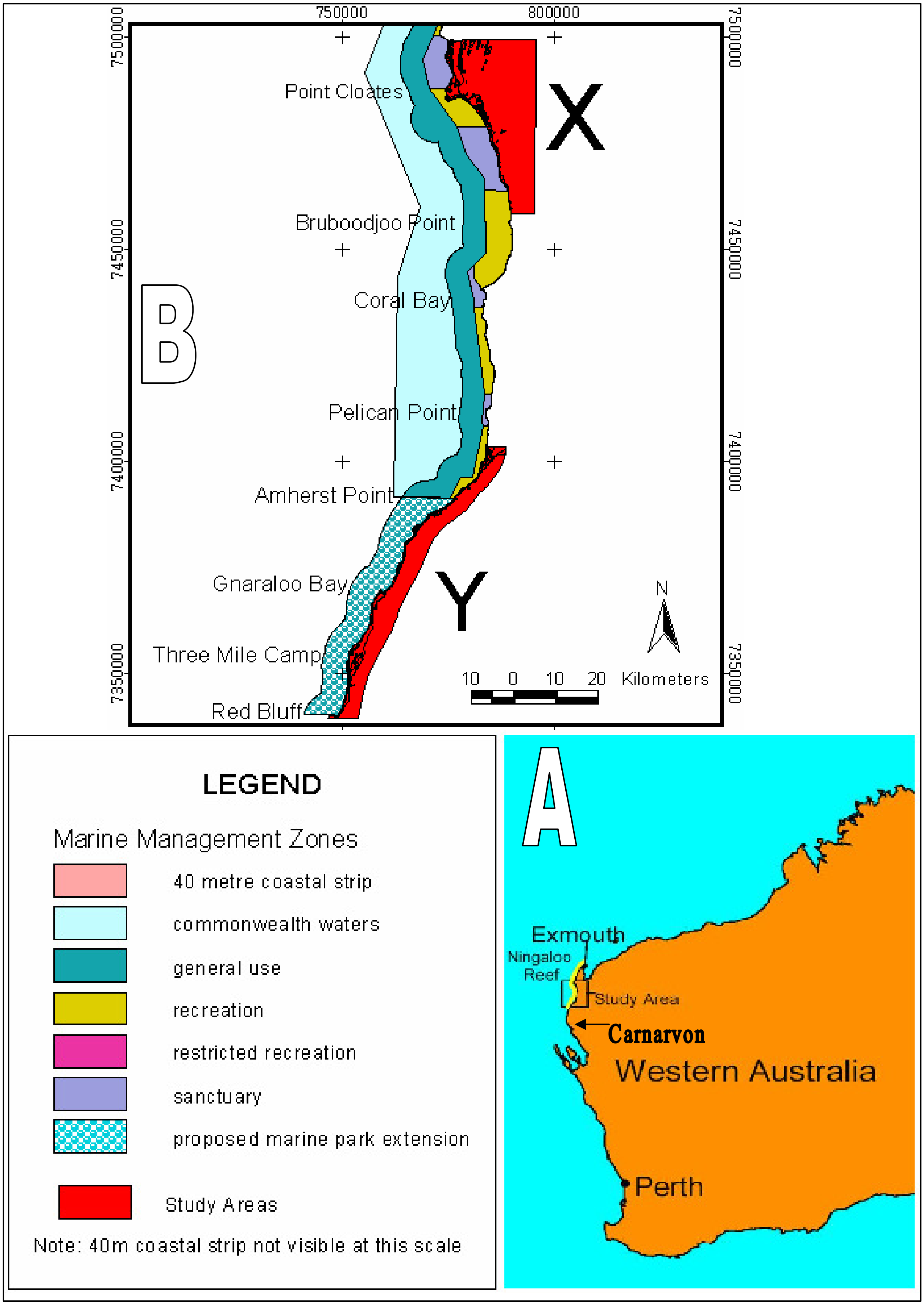


Figure 1-1. (A) Location of the Ningaloo Reef and (B) the two mapped areas.

terrestrial sedimentary systems, thus providing a modern analogue for the adjacent uplifted and preserved paleoreefs (Sanderson, 1997). The coastal plain adjacent to Ningaloo Reef provides evidence of coastal evolution, tectonic uplift, global sea-level changes, coastal aeolian processes, desert aeolian processes and karstic processes. Interactions between each of these controls have determined the geomorphology and stratigraphy of the region.

It has been recognised that the coast adjacent to Ningaloo Reef is under increasing pressure for recreation and tourism development (Shire of Carnarvon, 2001; Marine Parks and Reserves Authority, 2003). Environment degradation due to uncontrolled camping and access track development has been recognised as a particular problem (Shire of Carnarvon, 2001; Blackwell 2002). This study aims to describe and map coastal geology, and to document the nature of coastal degradation associated with the different land units.

The term substrate capacity was developed for the purpose 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.

A major planning process is currently being undertaken by government agencies regarding future development options for the coast adjacent to Ningaloo Reef. It is expected that the geological, environmental and geographic system (GIS) data produced in this study will form the platform for further research work and future planning strategies in the Ningaloo region.

1.1 Aims and scope

This study aims to describe the geology of the coastal zone and document the nature and extent of coastal degradation in two areas adjacent to Ningaloo Reef.

The specific aims are:

- To map the geology of the hinterland adjacent to southern Ningaloo Reef, with emphasis on two selected areas (Area X and Area Y refer to Figure 1-1-B).
- To describe the Late Tertiary-Quaternary coastal evolution of the study areas, with emphasis on the Holocene.
- To create a Geographic Information System (GIS) data base for geology, substrate capacity, coastal access, nodes of activity and management zones for the two study areas.
- To develop a system of substrate capacity to the region for incorporation into land management.
- To evaluate environmental risk areas within the two mapped areas.

The two areas of land that are focused on in this dissertation are predominantly under the tenure of pastoral leases and include the following pastoral stations (from north to south): Ningaloo, Bullara, Cardabia, Warroora, Gnaraloo and Quobba (Figure 1-2). The Ningaloo Marine Park currently extends to 40 m inland from the high water mark; however this distance is currently under review; see Figure 1-2 for the location of the two mapped areas.

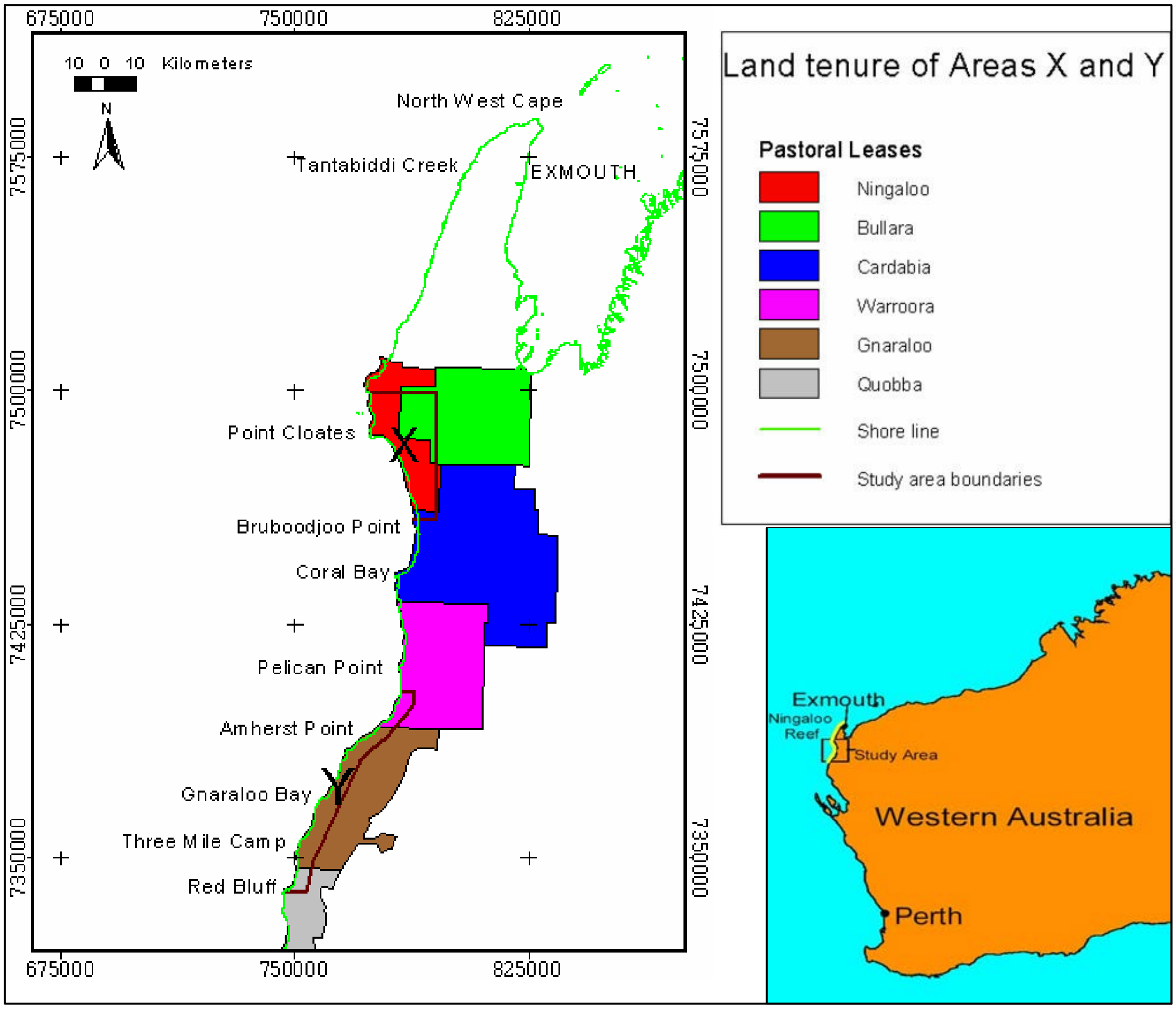


Figure 1-2. Land tenure of the coast adjacent to Ningaloo Reef.

1.2 Research Methodology

1.2.1 <u>Reconnaissance</u>

The Marine Park and Reserves selection working group (1994) proposed the extension of Ningaloo Marine Park to encompass the entirety of Ningaloo Reef. At present the Marine Park ends at Amherst Point in the south. However, the fringing Ningaloo Reef extends approximately 30 km further south to Red Bluff (see Figure 1-1-B).

Area Y

The coast between Red Bluff and Amherst Point has been the focus of limited scientific investigations and was chosen by the Department of Conservation and Land Management (CALM) as an area of investigation. This area was termed Area Y (Gnaraloo Region) for the purpose of this study; the mapping area was extended north to Alison Point due to a lack of knowledge of the area's geology.

Area X

The second study area (termed Area X) encompasses the majority of Ningaloo Station.

A significant area of Ningaloo Station has not been previously geologically mapped in detail. Ningaloo Station is situated in the centre of the Ningaloo Marine Park and is an increasingly popular holiday destination. Environmental pressures, such as land access tracks are a known problem for the station (Shire of Carnarvon, 2001), and warranted environmental geological investigation. The area, in particular the Ningaloo Homestead precinct, has been recognised as a potential development site for a coastal tourist node (Shire of Carnarvon, 2001; Department of Planning and Infrastructure, 2003).

The following aerial photo mosaics were utilized in digital format, for detailed photograph interpretation:

Area X: Orthorectified aerial photograph: Coral Bay-Exmouth Mosaic

egu+nin_20000800_utm49_gda94. 1:25,000 Ground resolution of 1.4 m

Area Y: Orthorectified aerial photograph: Red Bluff Mosaic

Nin+nre+rbp_19990700_utm49_gda94. 1:25,000 Ground resolution of 1.4 m

For interpretation purposes, and to assist in field work, enlargements at 1:10,000 were produced (including stereo pairs) and were printed on high resolution colour A3 sheets.

ASTER and Landsat TM imagery were also used in the initial stages to determine regional geological trends. Fire scars were evident by using ASTER images.
Aerial photo interpretation was used to determine preliminary geological boundaries, geomorphic units, coastal terrain and access tracks.

1.2.2 Fieldwork

Areas X and Y were the focus of a two and a half week field study. Within these two areas, the geology, geomorphology, substrate characteristics, environmental degradation and topographical features such as slope, drainage and vegetation from Areas X and Y were recorded. Stratigraphy was documented by field relationships, and via trench and shallow hole descriptions. Unconsolidated material and substrate was sampled at approximately 100 different localities for analytical and descriptive purposes. Land use, access and environmental degradation were verified, photographed and documented. Numerous ground traverses were also conducted. Geomorphology, lithology, sediment/rock type, slope stability and vegetation cover descriptions were completed across the areas. A number of handheld GPS localities were collected to verify aerial photo interpretations and also to estimate elevation (metres above sea-level).

1.2.3 Classification and Terminology

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 were attributed to each unit. The mappable units were therefore classified by a range of attributes.

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. “Land units” and “environment units” are suitable terms for systems which place a heavy emphasis on vegetation variations and are associated with an urban environment (Gonzalez et al. 1995). Blackwell (2002) developed a system of “land system units” which resemble the Gonzalez et al. (1995) principles, but based the terminology on a relatively natural environment where land units are largely defined by geological/ geomorphological characteristics. The Blackwell (2002) “land system unit” term will be utilised for the purpose of this investigation as 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 capacity (see 1.2.4) and land use characteristics. Land system units are therefore interchangeable with geological units and include important land management information. Chapter 6 of this report contains the land system unit descriptions.

The development of descriptions and nomenclature for mapping units was completed with the end-use and probable user in mind. These users include Marine Park managers, state agency planners and land managers such as station operators who will utilise the data for land management and research purposes.

1.2.4 Substrate Capacity Classification

Substrate capacity is a term developed for the purpose of this study to enhance land unit descriptions and creates a land classification scheme useful for land management purposes. It emphasises the ability of the land system unit's capacity to withstand natural and anthropogenic impacts on substrate characteristics. It incorporates a combination of principles from Blackwell's (2002) "Substrate Capability Index" and Maanaki Whenua Landcare's (2001) "Land Use Capability Module" with additional factors unique to the Ningaloo coastal region. Terminology evolved during this study and the previous Ningaloo coastal study by Blackwell (2002). Substrate capacity can be summarised as:

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

A scale of 1 to 5, as outlined in Table 1-1, was used to define the Substrate Capacity Index (SCI). The Index is dependent on, and was developed by, a qualitative and quantifiable assessment of land unit characteristics. These included; rock type, unit thickness, stratigraphy, vegetation cover, topography, slope stability, constituents, consolidation, drainage and weathering. Anthropogenic impacts in this region are predominantly caused by access tracks and recreational camping activities, the most obvious and destructive impact being the proliferation of access tracks and vegetation clearing for camping sites. Inadequate waste/rubbish disposal facilities and the denudation/destruction of habitat, caused by firewood collection are also impacts on the region. Other human impacts include activities associated with station work such as damage due to unrestricted stock access, fire management, land access and other land

Table 1-1. Unit characteristics used for the development of a substrate capacity index (SCI) for coastal units adjacent to the Ningaloo Reef (modified after Blackwell, 2002).

SCI	1	2	3	4	5
	Very Low	**Low**	**Medium**	**High**	**Very High**
Characteristics					
Consolidation/ Constituents	Unconsolidated, usually mobile calcareous sand.	Unconsolidated calcareous sand.	Semi consolidated to compacted sand.	Semi consolidated to compacted calcareous sand.	Completely consolidated. (Limestone)
Slope/ Topography	Steep slopes on undulating topography.	Variable; steep slopes on undulating topography.	Medium slopes, gently 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.	Moderate to variable thickness units over limestone base.	Moderate to low thickness units over limestone base.	Composed of exposed limestone.
Vegetation Cover	None to very sparse.	Sparse grassland and coastal scrub.	Moderate cover of grassland and scrub including established trees.	Moderate to high cover of scrub, grasslands and small trees.	High cover of scrub, grasslands and small trees.
Drainage	Well drained, little dissection.	Generally well drained; Poor drainage in saline flats/deflation basins.	Depressions prone to flooding; local incision exposing limestone.	Rare incised channels.	Occasional entrenched drainage channels/creeks.

management activities.

Naturally occurring impacts include tropical cyclones (extreme rainfall, associated run off and strong winds), drought conditions, tsunami impacts, fire, sea-level variations, extreme storm events and loss of vegetation associated with these impacts.

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 the GIS work to enable data to be integrated with existing CALM data bases. Geological boundaries and access tracks were digitised on a base layer of orthorectified aerial photographs with a ground resolution of 1.4 m. The scale of view during the geological boundary digitising varied from 1:2000 to 1:3000; the access tracks were digitised using views of 1:500 to 1:1500. These boundaries were checked in the field using handheld GPS locality readings.

To achieve the desired spatial data analysis (Figure 1-4) for the delineation of environmental risk zones, two Arcview extensions were used. The 'Polygrid' extension was required to overlay a measured grid onto the aerial photographs (to enable data analysis per grid cell) and the 'X-tools' extension was used to calculate individual cell areas and perimeters. These extensions are available free of charge via the ESRI website at www.esri.com.

1.2.6 Data Analysis

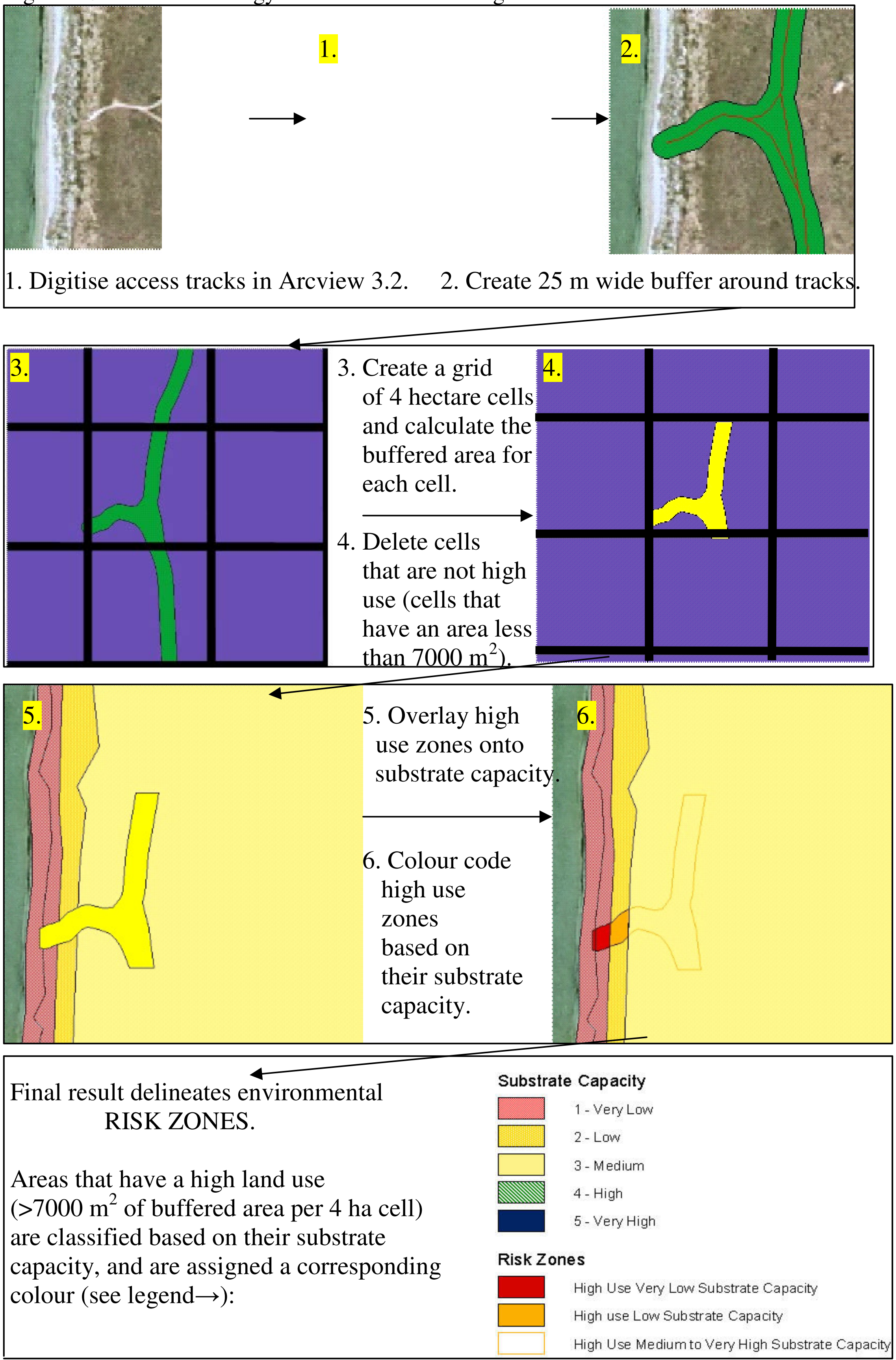
Data analysis consisted of evaluation of the aerial extent of high land use zones and high-risk zones within the two mapped areas. Track density was used as a measure of land use. In order to measure the track density and then delineate high use zones the following method was employed (see Figure 1-3).

The access track mapping that was created as line layers in Arcview was selected.

A 25 m wide buffer was then created along the extent of the original access track line theme. Following this a four hectare cell (200 m by 200 m) grid was created and applied to the study areas. The area of the buffered area was then calculated for each 4 hectare cell. Cells that contained a buffered area of less than 7000 m^2 were deleted, thus the remaining cells all had a buffered track polygon area of 7000 m^2 or higher. The reasoning for a cut off of 7000 m^2 and a buffer of 25 m is described in Appendix 1. A polygon area of 7000 m^2 equates to a track distance 280 m in length. The polygons in these cells were deemed high use zones, and were overlayed on top of the substrate capacity theme/map (in Arcview). A colour coding system was then applied to the high use zones based on the land unit's substrate capacity.

These high-use polygons were utilised to gain a quantitative assessment of the area of each land unit affected by current high land use. Areas of high use and a low substrate capacity (SCI of 1 or 2, see 1.2.4) were deemed to be **risk zones**. Erosion caused by vegetation degradation is the major environmental concern in the risk zones.

Figure 1-3: The methodology of the delineation of high use areas and environmental risk zones.



1.2.7 GIS Limitations

The GIS derived risk zones do have limitations. The grid is placed randomly over an image of the area; however depending on its position a small percentile of potential environmental risk zones may go undetected (Figure 1-4). The error is difficult to quantify, however based on visual assessment of the entire study areas it would appear to be less than 5%. The risk zones also vary to a minor degree depending on cell size and buffer width. Refer to Appendix 1 for reasoning for the specific values.

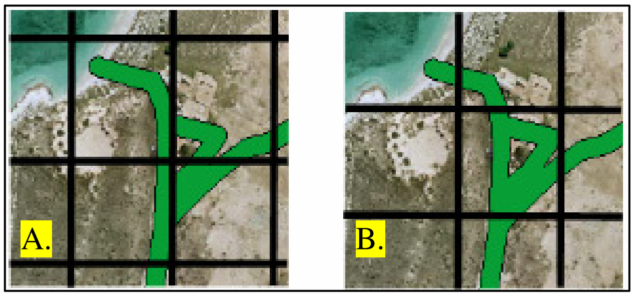


Figure 1-4: Example of a potential grid limitation (example A. would not detect a cell of high density, however example B. would).

1.2.8 Sample Preparation

Thin sections and grain mounts collected from Areas X and Y were prepared at CSIRO ARRC, Exploration and Mining Sample Preparation Lab. Owing to the friable nature of many of the sedimentary rocks it was necessary to coat the whole rock samples with an araldite resin. Once the araldite resin had dried and infilled the surface cavities of the rock in a desiccation chamber, the samples were cut to shape and flattened using a diamond grinding wheel to remove excess resin. This was followed by 20 minutes on a lapping machine (30 micron silicon carbide grit polisher in water). The samples were then mounted on a glass slide and ground down to between 0.5→1 mm thickness before trimming to a thickness of 30 microns on the lapping machine on a vacuumed jig (30 micron silicon carbide grit polisher in water). The grain mounts were prepared by the same method as the thin sections. The sediment samples were packed loosely. Following the final lapping process the grain mounts were polished with 1.5 micron polishing powder for 2 hours on a cloth lap polishing machine.

2. REGIONAL GEOLOGY

2.1 Geology

The coastal plain adjacent to the Ningaloo Reef is situated within both the Exmouth and Gascoyne Sub-basins of the Carnarvon Basin (Hocking, 1990). The Carnarvon Basin is a 1000 km long, elongate Phanerozoic basin along the western and north western coastline of Western Australia located between latitudes 20ºS and 28ºS. It is epicratonic, faulted and gently folded, and flanked by Precambrian rocks to the east (Hocking et al., 1987). The geological history of the basin has been dominated by intermittent regression and transgression of the sea (Condon, 1965) and a rather tectonically complex setting from the Silurian to the Tertiary (Thomas and Smith, 1974). The Exmouth Sub-basin is part of a south eastern set of troughs comprising the Barrow and Dampier Sub-basins located in the north of the Carnarvon Basin; it encompasses the Cape Range area. The Exmouth Sub-basin is a half graben formed by shallowly dipping detachment faults. The mainly Palaeozoic Gascoyne Sub-basin is elongate north-south and is gently tilted to the west. Rifting commenced in the Northern Carnarvon Basin in the Early Jurassic, with the north-north easterly trending Exmouth Sub-basin superimposed over the older northerly tectonic grain of the Gascoyne and Merlinleigh Sub-basins (Malcolm et al., 1991).

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 aeolian and marine sediments (van de Graaff et al., 1980). The ranges indicate that the coastal margins have experienced tectonic activity during the Cenozoic. The coastal plain adjacent to the Ningaloo Reef flanks the Cape Range and Giralia Anticlines (Figure 2-2). Quaternary non-marine superficial deposits now cover most of the Carnarvon Basin.

The backbone of the Cape Range peninsula occurs as a prominent northerly trending range of hills about 80 km long and 20 km wide. The cape rises in a steep escarpment on the west side, and slopes more gently towards Exmouth gulf in the east, with a maximum elevation of 314 m at Mt. Hollister (Allen, 1993). The predominantly calcareous range is deeply dissected with related alluvial fans occurring on the coastal plain. Underground caves and karst systems are also abundant. The Cape Range Group, a 500 m thick sequence of Palaeocene-Miocene rocks, forms the core of the range. Up to 10,000 m of Phanerozoic rocks underlie this (Hocking, 1990). The west side of Cape Range is characterized by a series of emergent terraces (Figure 2-1); the youngest of these is the Tantabiddi Terrace which has been dated at 125 ka BP (van de Graaff et al., 1976). The interaction of sea-level change and range uplift has resulted in the development of this sequence (Wyrwoll et al., 1992).

South of the Cape Range lies the Giralia Range (Figure 2-2). The district was subjected to a period of major block-faulting and deformation in the Jurassic and Early Cretaceous, which signalled the onset of complete continental break-up (Thomas and Smith, 1974). Following extensive sedimentation, the district was again subjected to tectonic stress in the Late Miocene (Payne et al., 1980). This resulted in the formation of

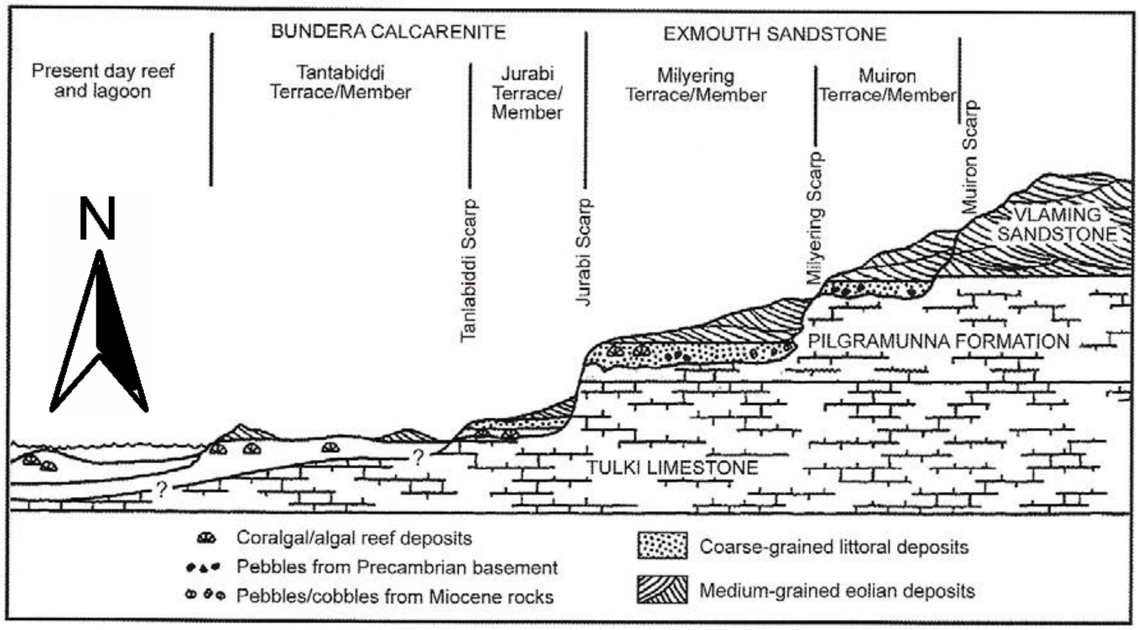


Figure 2-1. Uplifted coral reef complexes fringing the western flank of Cape Range terrace (after van de Graaff et al., 1976). Scale 1:5.

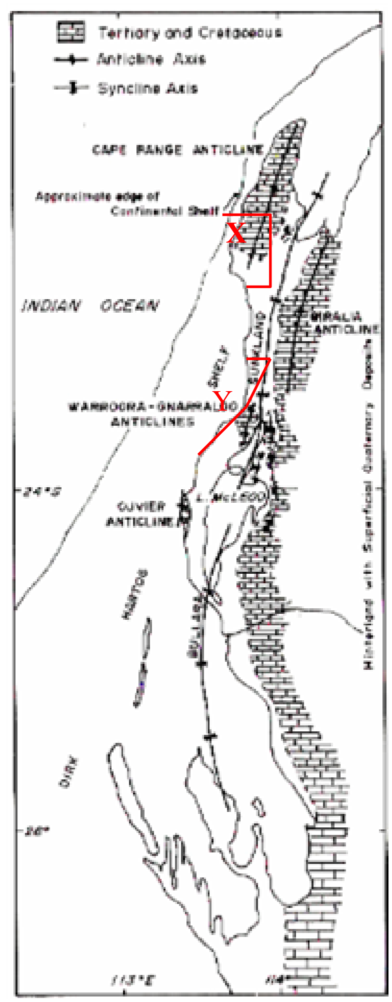


Figure 2-2. The major tectonic elements in the Shark Bay To Exmouth Gulf region of the Carnarvon Basin (after Logan et al., 1970).
Note the localities of the Cape Range Anticline and the Giralia Anticline as they are adjacent to Area X and Y respectively.

a series of anticlinal folds on the older normal faults, the largest of which is the Giralia Range. It extends for 120 km and rises to 170 m above sea-level, exposing sediments from the Late Cretaceous to the Late Tertiary. The South Giralia Range occurs between Allison Point and Cape Farquar, but is too far inland to be included in Area Y. Both sides of the Giralia Range are deeply dissected. On the western side, several low relief narrow gorges extend seaward to the coast carving a channel through limestone terrain as visible in the northern sector of Area Y.

East of Area Y lies Lake McLeod, an area of flat saline plains, in a low-lying area subject to regular inundation. The shape of Lake McLeod was largely determined by the gently dipping Tertiary anticlines which flank the lake to the east and west.

Offshore, the fringing Ningaloo Reef, located to the west of Cape Range, dominates oceanographic processes. The currents influenced by the reef determine both marine and sedimentary systems and provide a modern analogue for the adjacent uplifted and preserved paleo-reefs (Sanderson, 2000).

2.2 Geological Evolution

The Ningaloo Reef and Range Region are located on the most north-western point of the Australian continent and record the geological evolutionary processes on this ancient continental margin. The region is believed to have been situated on the coastline of the Tethys Sea prior to the break up of Pangea (Humphreys, 1993). The presence of raised fossil reefs in the Cape Range region is due to both uplift and change in sea-level. The higher fossil reefs on Cape Range are graphic evidence of episodic local tectonic uplift on the western margin of the continent of Australia.

A major reef complex is also exposed on the coast south of Cape Range, and is interpreted as a marker of a higher sea-level during the last Pleistocene interglacial period. The lowest lying fossil reef has a strong faunal overlap with the adjacent modern living reef. However, some specific differences provide clues to evolving marine reef fauna (Wyrwoll et al., 1992). The geological evolutionary significance of these two types of fossil reefs (uplifted and sea-level change), is greatly enhanced by the fact that they not only occur together but are also immediately adjacent to the living fringing reef. This feature illustrates the evolution of a coral coastline in response to changes in sea-level, through the combination of uplift of land and climate induced changes in global sea-level (Hitchcock, 2001).

2.2.1 Karst Systems

The Cape Range is deeply incised by dendritic intermittent streams which have sculptured a rugged topography (Figure 2-3). Beneath this arid exterior of weathered limestones lie karstic features such as sink holes, caves and solution cavities. The caves provide a cool humid atmosphere and support life forms called ‘troglobites’, animals adapted over millions of years for underground existence (Humphreys, 1993). Below the caves lies a fresh water aquifer of low relief, saline at its edges under the coastal plain from tidal movement of seawater up to 3.5 km inland from the adjacent Ningaloo Reef (Australian Marine Conservation Society, 2002). Within this aquifer and salty interface are a unique group of sub-terrainean aquatic animals, collectively known as ‘stygofauna’. These stygofauna and troglobites are useful in reconstructing the geological evolution of the region, and are known to exist in Area X (Knott, 1993).

Figure 2-3. Deeply incised dendritic intermittent streams in the Cape Range have sculptured a rugged topography. Photograph taken from Charles Knife Road.

Troglobites and stygofauna are of different origins. The closest relative to the aquatic stygofauna lie either side of the North Atlantic (Humphreys, 1999). This wide distribution of related species today suggests a common origin over 180 million years ago, when Pangea, on the shores of the Tethys Sea [which persisted from the Triassic (200 Ma) until the late Eocene (40 Ma) (Smith and Briden 1977)], broke up, separating the continents of Gondwana and Laurasia (Knott, 1993). It can be concluded that the common ancestors of stygofauna were separated by tectonic plate movement, which accounts for their present distributions.

The closest living relatives of the cave troglobites are animals found in the litter on the floor of tropical and southern temperate forests of Australia (Australian Marine

Conservation Society, 2002). The presence of troglobites in the present day arid climate of the Cape Range region indicates that wet and humid rainforest conditions must have existed within the past 20 million years, when the Cape Range limestones were deposited and the caves began to form. Since then, they have adapted and evolved to a strictly subterranean life, hence becoming a living indicator of past climates. Antecedents of all elements of the Cape Range stygofauna are regarded to have evolved in the Tethys Sea, and invasion into groundwater of the peninsula is considered to have occurred in situ throughout the whole sedimentary basin where the peninsula developed (Knott, 1993).

The cave system preserved on Cape Range has developed in response to geological, climate and eustatic factors. The main geological factors predisposing the area to karst development are the presence of relatively pure and permeable Trealla and Tulki Limestones (Table 2-1); the presence of the underlying relatively impermeable Mandu Limestone, and local jointing and faulting, enabling solution development of piping and flow paths within the limestone (Allen, 1993). It is predicted that karstification and initiation of the cave system probably commenced in the Late Miocene to Early Pliocene when the range emerged as an island, under tropical conditions. Since then the cave system has extended into the coastal plain sediments, and has been partially drowned by rises in sea-level (Allen, 1993).

Table 2-1: Generalised near surface stratigraphic sequence of the Cape Range region. Illustrating the stratigraphic location of the Trealla, Tulki and Mandu Limestone (modified after Allen, 1993).

AGE	FORMATION	THICKNESS (m)	LITHOLOGY	COMMENTS
Holocene	Various minor units	<20	Aeolian deposits, alluvium, colluvium, littoral deposits.	Sediments preserved
Pleistocene	Bundera Calcarenite	<20	Calcarenite and calcirudite.	on marine terraces
Pliocene	Exmouth Sandstone	<20	Quartzose calcarenite.	and coastal plain.
		UNCONFORMITY		
M-L. Miocene	Vlaming Sandstone	65	Calcarenite: well sorted, medium, quartzose, aeolian.	Restricted to western side of Cape Range.
M. Miocene Cape Range Group	Pilgramunna Formation	25	Calcarenite: well sorted, quartzose, fine-very coarse with interbedded beds of packstone and boundstone.	Lateral equivalent of the upper Trealla Limestone; mainly restricted to western side of Cape Range.
	Trealla Limestone	20	Packstone/grainstone: bioclastic fossiliferous, high carbonate content.	Lateral equivalent of the Pilgramunna Formation; exposed in western and northern part of Cape Range.
E. Miocene - L. Oligocene	Tulki Limestone	90	Packstone/grainstone: foraminiferal marly packstone, and grainstone.	Lateral equivalent of upper Mandu Limestone, caves mainly developed in this unit.
	Mandu Limestone	280	Calcarenite/calcilutite/calcisiltite:chalky to marly fossiliferous, notable large Lepidocyclinid foraminifera.	Locally exposed in valleys on range between Exmouth and Learmonth.

2.3 Regional Geomorphology

The explanatory notes to the Yanrey-Ningaloo 1:250,000 map sheet describe ten major physiographic units, 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 Graaff et al., 1980). These three regions were later renamed the Macleod Region, Marrillia Region and the Ashburton Plain, respectively, by Hocking et al. (1985).

Van de Graaff et al. (1980) described the immediate coastal area adjacent to Ningaloo Reef as sand dunes or calcareous coastal dunes with calcareous duricrust to the south; also described are the coastal terraces and shoreline scarps on the western coast of Cape Range. The entire coast adjacent to Ningaloo Reef lies within the Macleod physiographic region (Hocking et al., 1985). This region encompasses the Exmouth Peninsula south to the Gascoyne River (Figure 2-4) and is described as "… a series of variably dissected anticlinal domes (Tertiary) separated by low-lying areas in filled by Pleistocene marine and aeolian sediments" (Hocking et al., 1987).

The coastal plain adjacent to Ningaloo Reef slopes gently to the coast and is characterised by low relief, and large, gently undulating sand plains. The coastal dunes are composed of predominantly sedimentary surfaces which were intermittently deposited in a marine shelf environment (D.A. Lord and Associates, 2000). Near the coast, limestones are overlain by coastal dunes and beach ridges. Inland, the district is characterised by older longitudinal dunes of terrigenised compact sand over limestone.

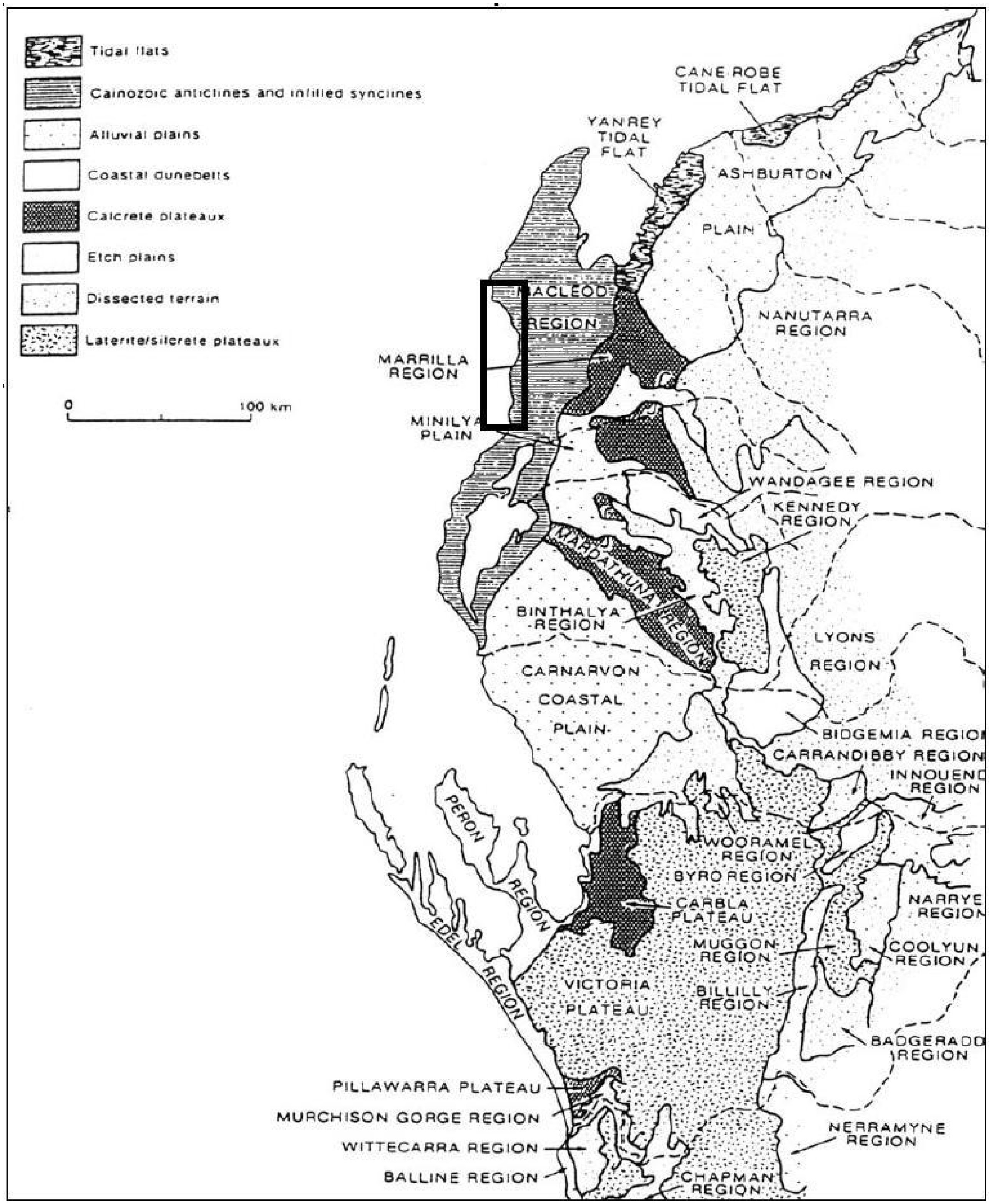


Figure 2-4. The physiographic regions of the onshore Carnarvon Basin (after Hocking et al., 1987).The black box delineates the study area.

3. PHYSICAL PROCESSES

Physical processes have resulted in the sculpturing of the coastal geomorphology along the Ningaloo coastline. Factors such as climate variability, offshore currents and extreme weather events continue to influence the intricate sediment supply to the region.

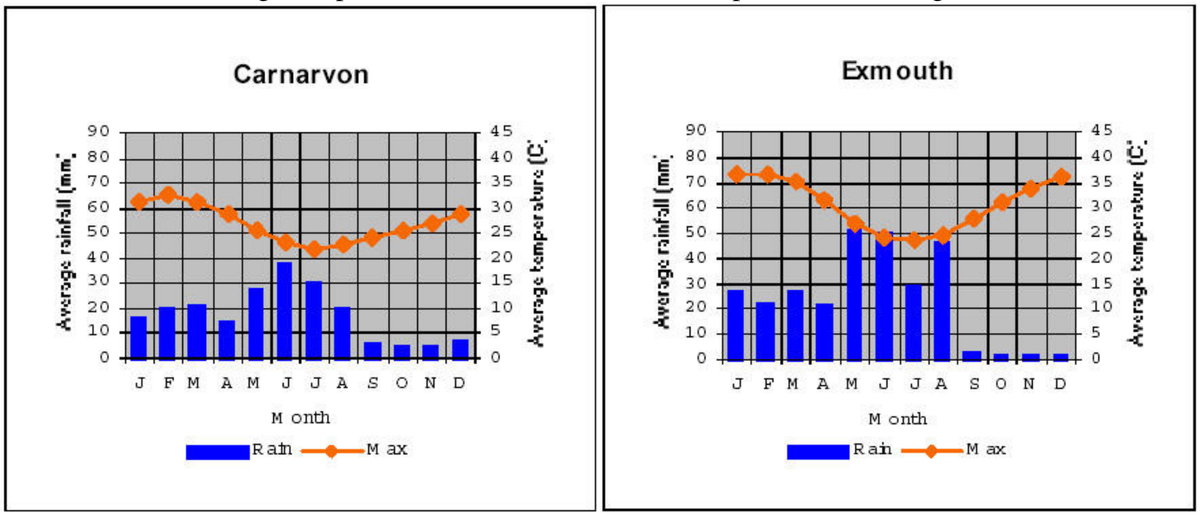
3.1 CLIMATE

3.1.1 Present Climate

The present climate of the Ningaloo coastal region varies from warm, semi-arid in the south (near Red Bluff) to hot arid in the north (near Cape Range). In January, average daily minimum and maximum temperatures for the coast adjacent to Cape Range are about 23°C and 37°C, and in July, 14°C and 24°C (Table 3-1) (Bureau of Meteorology, 2003). The fact that the coast experiences mild winters and warm to hot summers makes the area an attractive tourist destination throughout much of the year. The coast adjacent to southern Ningaloo Reef (near Red Bluff), experiences one to two degrees cooler daily temperatures than those adjacent to northern Ningaloo Reef, near Cape Range. The region receives both winter (frontal) and summer (cyclonic) rains averaging 300 mm per year; however this is considerably exceeded by the mean annual evaporation of over 2,500 mm (Western Australian Ministry for Planning, 1996). The rainfall from year to year is highly variable due to the impact of extreme weather events such as tropical cyclones and major storms. In many years the majority of annual rainfall (associated with a tropical cyclone or extreme storm event) is received within a few days.

The mean annual wind speed at Carnarvon is 6.1 ms^{-1} with a mean wind direction of 184º (Hearn and Parker, 1988). During winter, the coast adjacent to Ningaloo Reef receives south easterly winds (with south-westerly sea breezes), derived from the

Table 3-1. Average Climate Graphs (Bureau of Meteorology, 2003). The orange line represents the maximum average temperature (ºC), and the blue bars represent the average rain fall (mm).



subtropical anticyclonic high pressure belts which control much of the state's weather. During the remainder of the year, the wind direction alternates between the south and southwest with speeds increasing during the day with the diurnal sea breeze oscillation (Sanderson, 1997). Hence a southerly wind prevails on the Ningaloo coast all year round (with the exception of cyclonic and storm winds) resulting in the present orientation of aeolian deposits and contributing to the flow regime of northerly lagoonal currents.

3.1.2 Cyclones

The coast adjacent to Ningaloo Reef is prone to extreme natural physical processes. The North West coast is prone to cyclones and tsunamis. Of these, severe tropical cyclones are more common, occurring at a frequency of one every 3-4 years (Bureau of

Meteorology, 1998). On the 21st of March 1999 the centre of tropical cyclone Vance passed within 20 km of Cape Range. Vance produced a record wind speed for the Australian mainland of 267 km/hr at Learmonth, 35 km south of Exmouth. The strong winds associated with tropical cyclones are predominantly from a northerly direction. Table 3.2 outlines the frequency of cyclone impacts at Learmonth, on the east side of Cape Range. Tropical cyclones and associated storm surges, combined with high tide have caused severe erosion at the beach front at Exmouth and along the west coast of the Cape Range peninsula (Barrett, 1999).

During summer, tropical cyclones may develop near the coast bringing high rainfall in association with extreme wave energy and very strong winds to the coast. These conditions have impacts on the coastal morphology that persist through the more quiescent weather conditions (Sanderson, 1997). Evidence that tropical cyclones exert a significant influence on formations of the coast includes erosion and reworking of the immediate coastline (see Figure 3-1) and the presence of relatively high northward facing foredunes.

3.1.3 Paleoclimate

Within the study area, the climate throughout the Quaternary (i.e. both Pleistocene and Holocene) has played a significant role in coastal processes and in the development of sedimentary products via agents such as high evaporation rates coupled with limited rainfall, cyclonic storms, wind, waves and the limited sediment delivery to the coastal zone. The coastal stratigraphy and geomorphology suggests aridity was intricately

Table 3-2. Cyclone severity categories, typical effects and occurrence frequencies (adapted from Bureau of Meteorology, 1998).

Category	Maximum Wind Gust (km/hr)	Typical Effects	Number of times recorded at Learmonth (1910-2003)
1	less than 125	Negligible house damage. Minor damage to crops, trees and caravans. Crafts may drag moorings.	**22**
2	125 - 170	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Small crafts may break moorings. Risk of power failure.	**10**
3	170 - 225	Some roof and structural damage. Some caravans destroyed. Power failure likely.	**2**
4 (e.g. Tracy)	225 - 280	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failure.	**0**
5 (e.g. Vance)	greater than 280	Extremely dangerous with widespread destruction.	**1**

Figure 3-1. Evidence of cyclonic activity on the coast based on the large block displacement (Area Y: 3 km south of Three Mile Camp). Note two people in the top right hand corner for scale.

involved in the sedimentation, geomorphic evolution and pedogenic and diagenetic alteration of this coastal zone throughout the Holocene and Pleistocene (Semeniuk, 1995).

Wyrwoll (1993) gave a review of paleoclimatic events in the Cape Range Region. He concluded that the closing stages of the Tertiary were characterized by a wetter climate than present. By middle Pleistocene, a more arid, interglacial climate regime had developed in the Cape Range. The precise timing of the onset of aridity is not known. The late Pleistocene (500 ka BP) climate was characterized by a series of glacial and interglacial stages. These stages consist of long (100 ka) glacial periods during which the climate was drier than during the Holocene, and short (10 ka) interglacials during which the climate was similar to, or wetter than today (Wyrwoll, 1993). It is generally accepted that the increased aridity during Glacial Maximum periods was due to a reduction in sea-level, reduction in the rate of tropical cyclones, and a slight decrease in ocean temperatures.

Palynological work by Van der Kaars and De Deckker (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 paleoclimate conclusions are based on floral assemblages derived from the pollen record. These records indicate 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 (Van der Kaars and De Deckker, 2002).

3.2 Oceanography

Oceanography varies the coastal morphology via a complex interaction between currents, tides, storm events, seiching and tsunamis. These seasonally variable factors influence sediment supply which directly results in morphological coastal features.

3.2.1 Regional Current System

The Leeuwin Current dominates the regional oceanography. The Leeuwin Current is a narrow (<100 km wide), warm southward flowing, low salinity stream that maintains the waters off the west coast of Australia at temperatures conducive to coral growth. It flows most strongly during the autumn, winter and early spring months when sea temperatures can be up to 4ºC warmer than adjacent oceanic waters. Sea surface temperatures range from 22ºC to 28ºC in the reef tract and are always tropical. The tidal range in the northern part of the reef is 1.7 m (Collins et al., 2002). The Leeuwin Current has an important influence on many biological processes along the coast, delivering larvae via its southward flow direction, whilst suppressing upwelling (Cresswell 1991; Hutchins and Pearce 1994). The continental shelf break in the northern reef at Ningaloo is at a depth of about 100 m and is located only 6 to 10 km offshore. This is the narrowest part of the shelf in Australia (Taylor and Pearce, 1999). The coastline veers sharply eastwards, south of Point Cloates, and the width of the shelf increases to over 30 km. The hot and arid coastal climate of the adjacent Cape Range region has a strong influence on Ningaloo Reef, where the annual average sea temperatures are 17ºC to 27ºC offshore (Collins, 2002).

3.2.2 Local Current System

The Leeuwin Current is not the sole current operating in the Ningaloo precinct. Current studies by Taylor and Pearce (1999) revealed a predominantly northward current along the reef front during the late summer and early autumn months, terming it the 'Ningaloo Current'. Together with the southward flowing Leeuwin Current, these two opposing currents generate a recirculation of water in the region (Figure 3-2). The Ningaloo counter-current (driven by strong south-southwesterly prevailing winds and sea breezes) may in fact determine the dispersal of coral larvae following the autumnal mass reef spawning, and may also be important in retaining planktonic biomass within the Ningaloo ecosystem (Taylor and Pearce, 1999).

The continental shelf is broader opposite Area Y, hence the tropical autumn-winter influence of the shelf-edge Leeuwin Current is less pronounced than further north (Marine Parks and Reserve Authority, 2003). In summer, the southern sector of the reef (Area Y) is influenced more by the cooler northward flowing Ningaloo Current than areas further north (Area X). These oceanographic differences result in the habitats and reef communities in the southern extent of the reef having greater warm-temperate affinities than the more sub-tropical northern parts of Ningaloo Reef (Marine Parks and Reserve Authority, 2003).

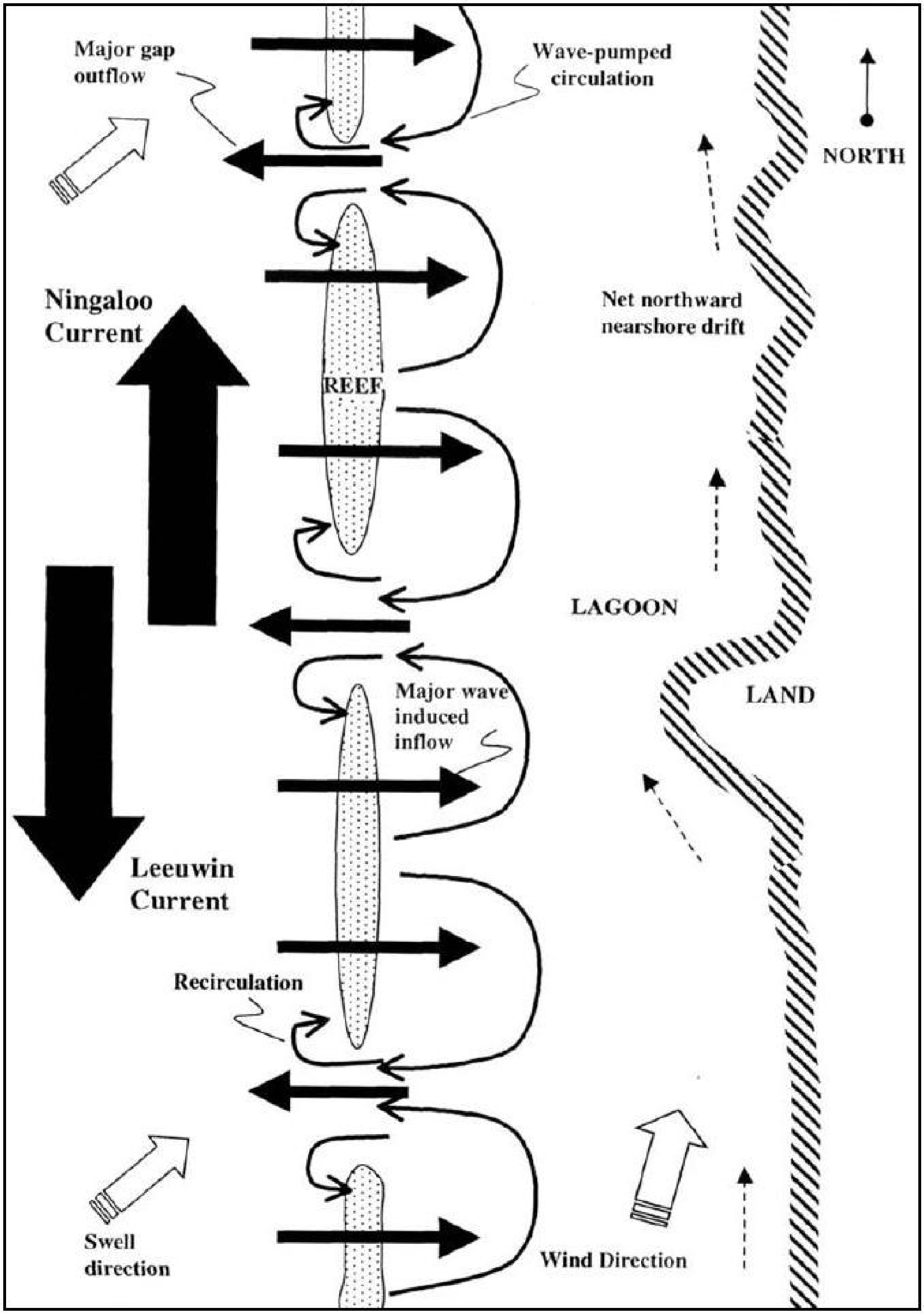


Figure 3-2. Schematic diagram of the main flow patterns believed to operate most consistently at Ningaloo Reef under the dominant forcing of wave-pumping, after (Hearn et al., 1988) and (D'Adamo and Simpson, 2001).

Figure 3-3 depicts the result of lagoonal flow patterns on coastal morphology in a complex lagoon in the Ningaloo Region (Area X). Note that the south most node of sedimentation is Point Cloates. At least four currents are operating across the continental shelf off Ningaloo: the warm Leeuwin Current flowing southward along the outer shelf/upper slope and driven by an alongshore pressure gradient (Godfrey and Ridgway, 1985); a seasonal wind driven northward inner-shelf counter-current, the Ningaloo Current (Taylor and Pearce, 1999); a wave/wind/tidally driven flow within the nearshore reef system (Hearn et al., 1986) and a current adjacent to the shore line, near shore drift. There tends to be a major perturbation in the flow of the Ningaloo Current at Point Cloates, where it appears to form characteristic counter clockwise circulation (D'Adamo and Simpson, 2001). The dynamic interaction between the Ningaloo and Leeuwin currents off Point Cloates may re-direct some of the water from the Ningaloo Current back towards the south. It has been proposed that this may bear an important relation with the relatively different diversities and abundances that exist between the plant and animal communities to the north and south of Point Cloates (D'Adamo and Simpson, 2001).

It is evident in Figure 3-3 that the major nodes of sedimentation are all in the lee of a protective reef crest, and the three bays correspond with reef passes, therefore clearly illustrating the dominant role that the Ningaloo Reef has played in controlling the coastal morphology. The wind direction also corresponds with the onshore transport direction of sediment, hence has dictated the shape and progradation direction of the parabolic dunes.

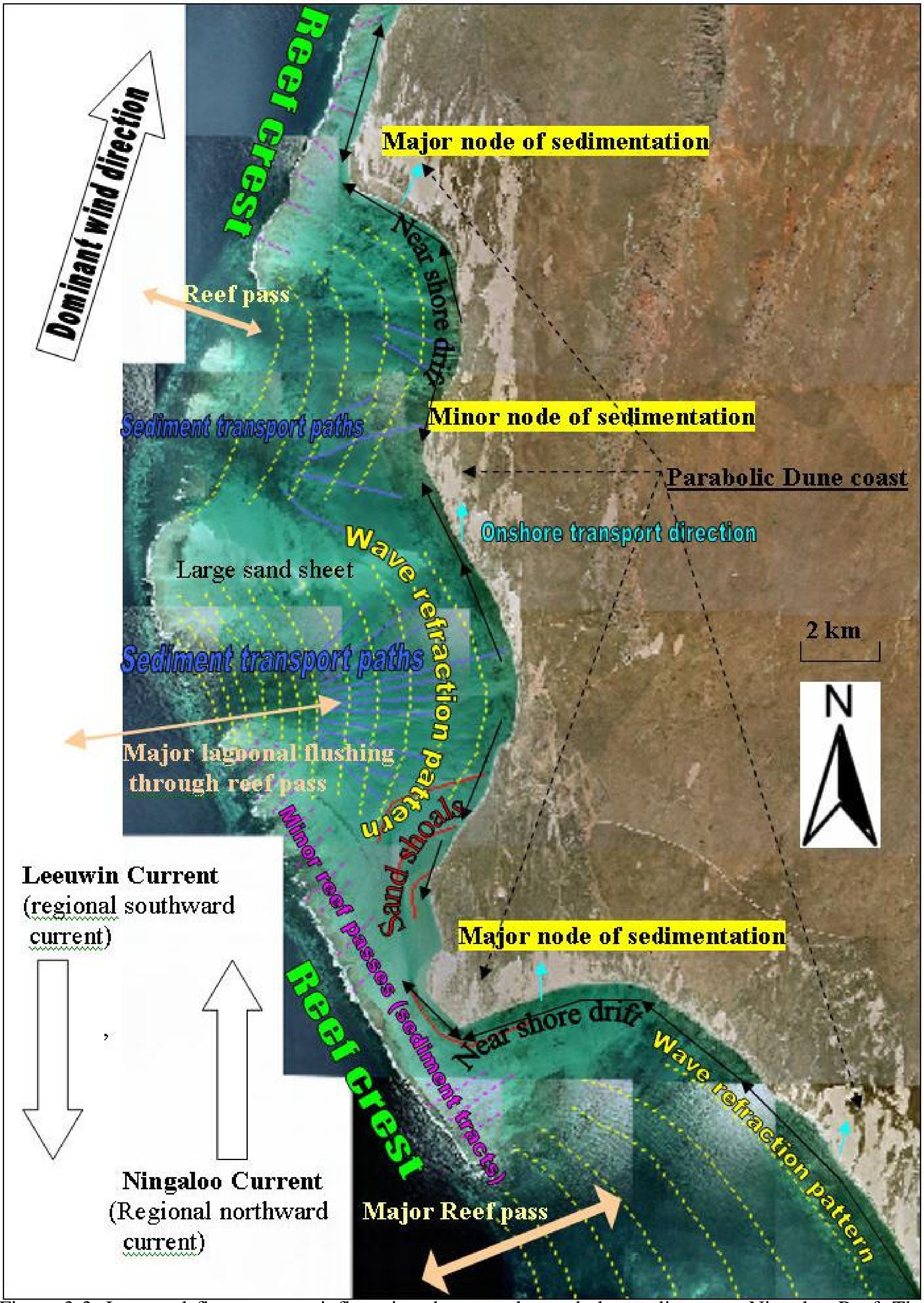


Figure 3-3. Lagoonal flow patterns influencing the coastal morphology adjacent to Ningaloo Reef. The aerial photograph clearly illustrates the hydrodynamic system and that sediment transport routes correspond to nodes of sedimentation. Depositional nodes commenced with late Holocene highstand accretion of parabolic dunes. The symbols are colour coded to their label, and the blue arrows indicate the direction of onshore transport. The photograph is situated in the north of Area X and is centred on grid reference: 776044, 7494585.

3.2.3 Tides

The Ningaloo coast experiences mixed diurnal and semi-diurnal mesoscale tides leading to a large variation in water level within the reef lagoon on a regular basis (Sanderson, 1997). The spring tide range at Exmouth is 1.8m. A considerable amount of water movement into and out of the lagoon is a result of the fluctuating water levels. This water enters and exits the lagoon via gaps in the reef. Significant water volumes also enter the lagoon by being forced over the reef crest at high tide. Circulation and transport of the reef's lagoonal waters is driven principally by waves, tides and winds. The overall circulation is dominated by wave-pumping of water over the reef tract, with the tides having a modulating role and with prevailing winds and sea breezes tending to drive near-shore lagoonal water predominantly northwards (D'Adamo and Simpson, 2001).

3.2.4 Tsunamis

Sudden movement in the earth's crust often results in Tsunamis, large amplitude ocean waves. Tsunamis may be initiated by a severe volcanic eruption or severe earthquake. The coastal impacts of tsunamis can be catastrophic; their impact can span hundreds of kilometres inland. In June 1994, an undersea earthquake south of Indonesia produced a tsunami that reached the North West Cape some two to three hours after the initial quake (Ministry for Planning, 1996). The wave resulted in mass fish strandings and large coral heads being washed onto the dunes.

3.2.5 Storm Surges

A storm surge is an elevated body of sea water typically 1 to 5 m above sea-level and 60 to 80 km wide. They are usually related to storm or cyclonic events that are typically associated with low atmospheric pressure and wind stress on the sea surface.

The reduced atmospheric pressure causes the sea to rise by about 10 cm per one hectopascal reduction in air pressure (Australian Institute of Marine Science, 2002). Storm surges at Coral Bay are estimated to be approximately 15% greater than at Carnarvon (Steedman Science and Engineering, 1989) based on wind, wave and atmospheric pressure components.

Figure 3-4. Geomorphic evidence of a storm escarpment (located in Jane Bay, Area X).

3.2.6 Seiching

Long-period standing waves, seiches, may occur inside the reef lagoon and cause a periodic rise and fall of the water level at the shoreline. Seiche motions are typically triggered by an impulse that may be related to: a storm surge; a change in wind direction/speed; or by periodic fluctuations in the wave heights breaking across the reef crest (DAL Science and Engineering, 2002).

3.3 Sea-level Variations

The geomorphology and stratigraphy of the coastal plain adjacent to the Ningaloo Reef has largely been controlled by Quaternary sea-level variations. Three major sea-level events have occurred during the Quaternary (Figure 3-5). The Last Interglacial transgressive phase occurred at approximately 125 ka BP, then after several minor regressions and transgressions, a regressive phase with a low stand occurred at approximately 20 ka BP, and the Holocene high stand, followed by a regression of +2 m to present day sea-level.

3.3.1 Last Interglacial Transgression

The Last Interglacial interval represents the last time global sea-levels were at or near modern levels, and by inference the last time ice volumes and global climatic conditions were similar to present day. Stirling et al. (1998) published U-series data with reliable dates showing that reef growth started contemporaneously at 128 ka ± 1 ka along the entire Western Australian coastline, while relative sea-levels were at least 3 m above the present level. Major episodes of reef building (both globally and locally along the Western Australian coast) were restricted to a very narrow interval from ~128 ka to 121 ka, suggesting that global ocean surface temperatures were warm and/or sea-levels were stable enough to allow prolific reef growth only during the earlier part of the Last Interglacial (Stirling et al., 1998). A possible reason for the abrupt termination of coral reef growth along the Western Australian coast could have been due to a sudden 'switch off' of the Leeuwin current.

The Tantabiddi Member of the Bundera Calcarenite extends continuously along the western margin of the Cape Range and re-emerges to the south of Cape Range at various localities between Three Mile Camp and Red Bluff. It is representative of the Last Interglacial Transgression. The Tantabiddi Terrace is the youngest terrace (ca 125 ka), and is of uniform elevation plus it lacks deformation, attesting to the tectonic stability of the region since this time (Collins et al., 2002). The Tantabiddi platform represents a former lagoonal fringing reef. Stirling et al. (1998) dated the Tantabiddi Last Interglacial Reef at 134.6±0.5 ka BP (U-Th series). This date correlates with other data obtained from other Last Interglacial Reefs such as Barbados (129.1±0.8) and Abrolhos (132.5±1.8) (Eisenhauer et al., 1996). The Tantabiddi Member is commonly exposed as notched terraces with the Last Interglacial reef 2-3 m above mean low water spring tide. Interpretation of this level most likely represents a minimum sea-level as the coral heads were probably growing 0.5-1 m below mean low water spring tide. The minimum sea-level recorded in this unit is therefore 4 m higher than today's sea-level (McCulloch and Esat 2000; Murray and Belperio, 1991).

3.3.2 <u>Last Glacial Regression</u>

An overall regressive trend prevailed after 125 ka BP until 20 ka BP. Within this regressional phase up to five relatively minor transgressions occurred. The regressive trend concluded at 20 ka BP with a sea-level of 125 m below the present level (Figure 3-5). The only onshore records of the regressive phase in the Cape Range region are the alluvial fan units such as the Mowbowra Conglomerate that developed as a response to both uplift of the Cape Range and sea-level fall (Wyrwoll et al., 1992). A number of comparable sea-level curves have been deduced from oxygen isotope dating. Figure 3-5 was primarily derived from oxygen isotope stages corroborated by dated coral terraces in Papua New Guinea (Chappell and Shackleton, 1986). These terraces have been preserved due to a considerable amount of uplift in the region.

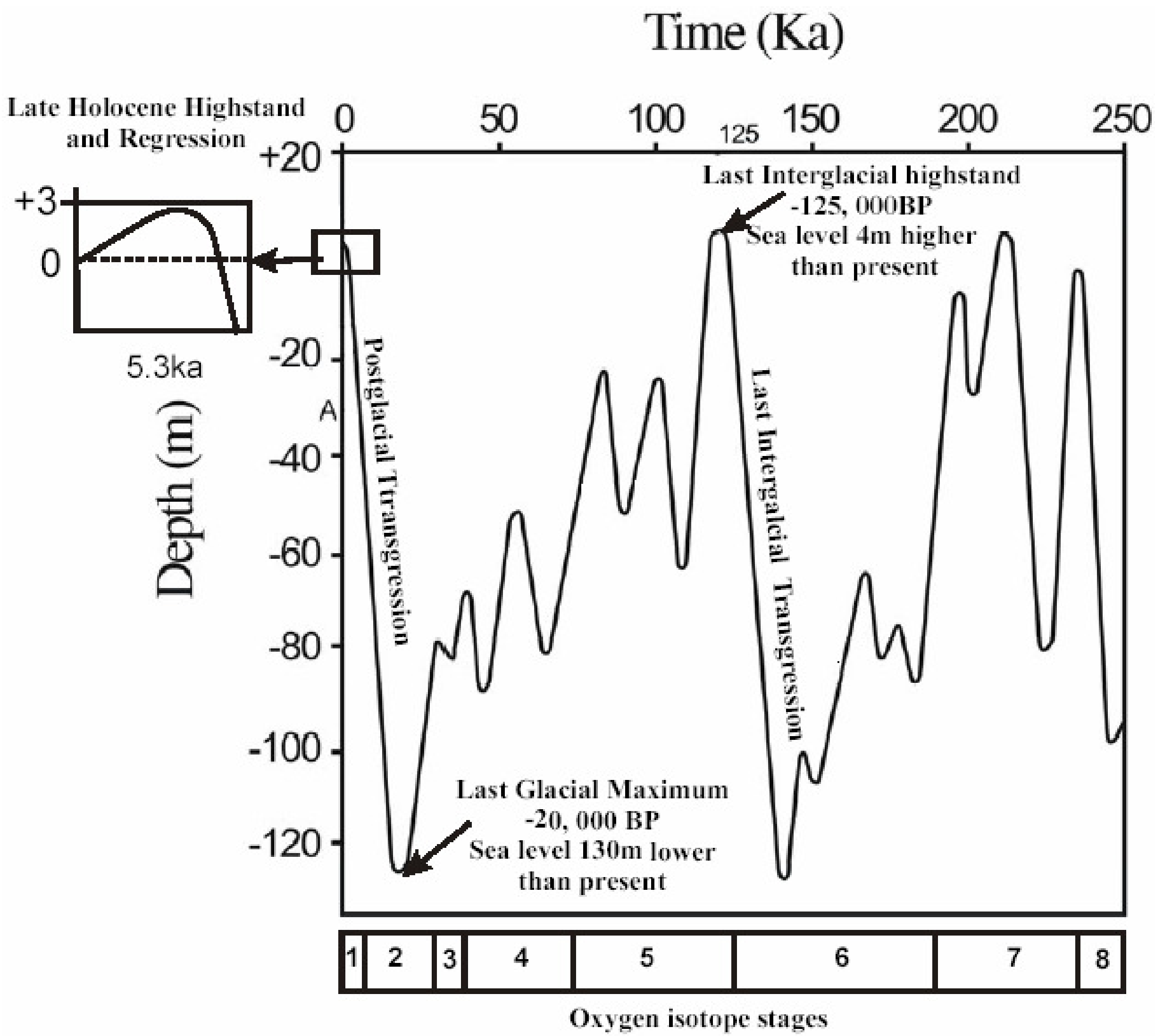


Figure 3-5: The record of Late Quaternary sea-level variations (modified after Chappell and Shackleton, 1986).

3.3.3 Last Glacial Maximum and Glacial Transgression

From 20 ka BP (from 125 m below present levels) until 5 ka BP a period of transgression occurred, terminating in the mid-late Holocene highstand (Figure 3-6). Yokoyama et al. (2001) reviewed sea-level observations and models for the Last Glacial maximum for the east Australian coast and derived a series of sea-level curves at four locations (Figure 3-6). No submerged shorelines to date have been studied in the Cape Range region. Dating of submerged shorelines at the Great Barrier Reef (1.8 ka ^{14}C BP at -133 m) corroborate these models (Yokoyama et al., 2001).

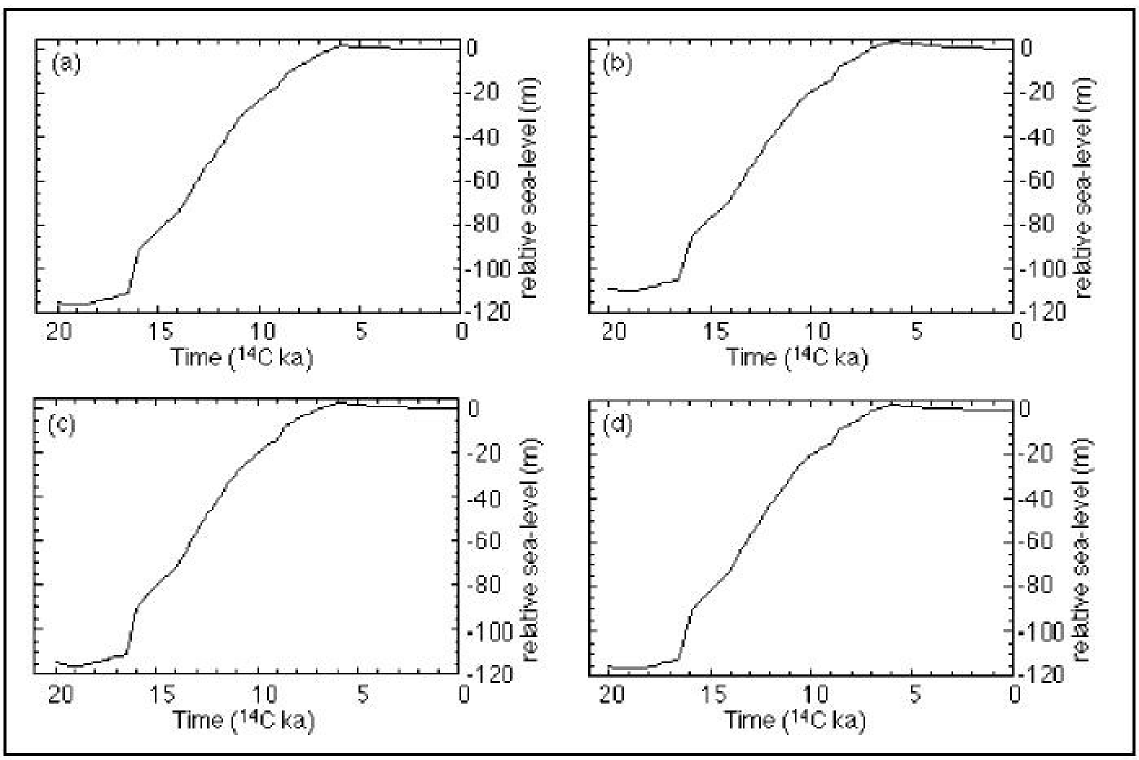


Figure 3-6. Predicted sea-level curves for: (a) Joseph Bonaparte Gulf, (b) Gulf of Carpentaria, (c) the Great Barrier Reef, (d) the Sydney coast. Produced using rigorous glacio-hydro-isostatic modelling. (after Yokoyama et al., 2001).

3.3.4 Middle to Late Holocene Highstand and Subsequent Regression

Baker et al. (2001) reviewed reconstructions of mid to late Holocene marine environments and sea-levels, obtained from the remains of relict inter-tidal or subtidal indicators, and derived Holocene sea-level fluctuations graphs from a number of coastal sites, including Rottnest Island (Figure 3-7). Rottnest serpulid tube worms were dated at 5050±290 years BP at 2.1 m above present sea-level. Richly fossiliferous shell beds of a palaeolagoon north east of Coral Bay town were dated, illustrating a marine embayment stranded by the Late Holocene transgression. Kendrick and Morse (1990) dated a cardiid bivalve *Acrosterigma dupuchense* obtained from a pale sandy coquina bed underlying a salt flat and yielded a natural radiocarbon age of 5230 ± 60 years. This is considered to represent the approximate time of cessation of marine exchange to the embayment. Similar marine embayments were located at numerous localities along the coast adjacent to Ningaloo Reef [e.g. on the coastal plain behind Gnaraloo Bay (Area Y) and Jane Bay (Area X)]. Figure 3-7 depicts the regression from 2.5 m at 500 BP to the present day level.

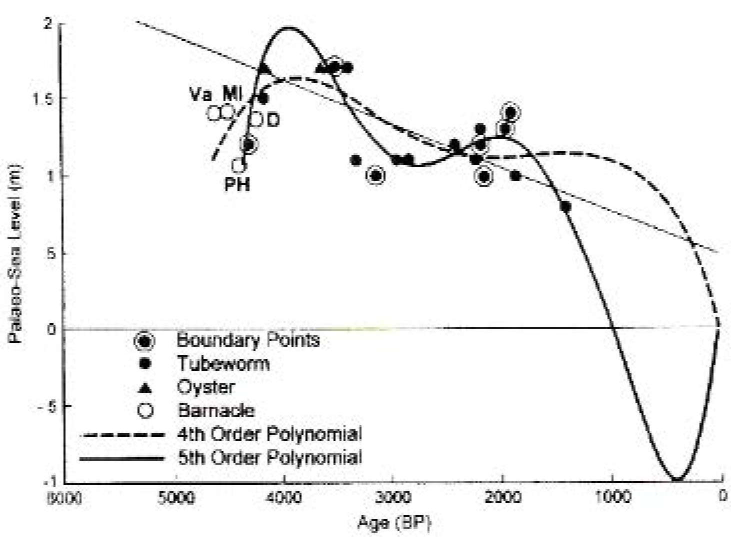


Figure 3-7. The linear and oscillating regression model of Australian sea-level data for the past 5000 years; marine reservoir corrected (after Baker et al., 2001).

4. ANTHROPOGENIC IMPACTS ON THE COAST ADJACENT TO NINGALOO REEF

This section is a summary of the anthropogenic impacts affecting the two mapped areas that were studied in this project. It includes a number of specific observations made during field work.

With increasing pressure on the state's coastal regions for development and recreational uses, the Ningaloo region is presently at the centre of a contentious planning and development debate. Future planning/management proposals such as "Future Directions" (Department of Planning and Infrastructure, 2003), "A framework for the review of the Ningaloo Marine Park management plan and consideration of adjacent proposed marine conservation reserves" (Marine Parks and Reserves Authority, 2003) and a government website on the Ningaloo Coast (www.ningaloocoast.wa.gov.au) are examples of public education/integration strategies that were launched in 2003. The coast adjacent to Ningaloo Reef is experiencing rapid increases in tourism, with visitors to the northern Gascoyne region estimated to be approximately 220,000 annually (Wood, 2003). Eighty per cent of all visitors came to the region to enjoy its warm winter climate and 73% came to fish (Wood and Dowling, 2002). With increased tourism comes increased environmental pressure from anthropogenic impacts. The major human impacts in the region are derived from recreational activities such as camping, four wheel driving, boating, fishing and surfing. These activities give rise to uncontrolled networks of access tracks, clearing of vegetation for camp sites, improper disposing of waste and numerous other minor impacts. There are also traditional impacts associated with pastoral leaseholder activities such as stock grazing (Figure 4-3-B), fire management, and land access. Based on a regional interpretation of aerial photography, Area X can be categorised as an area of moderate to high impact land use area, whereas Area Y contains moderate impact land use.

Vehicle access causes the greatest environmental impact on the coast (Figure 4-2). Access tracks have developed on an ad hoc basis, and are frequently uncontrolled, resulting in a proliferation of track networks. Significant degradation to this fragile environment has occurred in areas associated with nodes of activity, typically camping sites. The pastoral stations have attempted to implement controls with an aim of limiting the spread of access tracks, reducing litter and removal of vegetation (usually for firewood). Despite these efforts, access tracks and other environmental concerns are prevalent on most stations. All station managers charge a nominal fee for camping.

Camping site development and access tracks are the two major causes of coastal zone degradation (Figures 4-1 and 4-2). Degradation of the coastal plain is primarily caused by vegetation removal and soil disturbance triggered by vehicle tracks. Significant degradation occurs when the substrate is unable to withstand increased traffic. When this occurs denudation and erosion may affect large areas, leading to wind 'blowouts' of sediment. Every land unit responds differently to vehicle impact depending on its substrate characteristics (see substrate capacity index 1.2.4).

4.1 Gnaraloo Region (Area Y)

Within Area Y, formal accommodation is presently available at Red Bluff (camping and a limited number of basic shacks), Three Mile Camp (camping) and Gnaraloo Homestead (chalets). Informal camping is occurring at numerous localities in the northern quarter of Area Y on Warroora Station (Figure 4-1-D).

The coast where the informal camping is occurring (Warroora Station) is generally highly fragile and susceptible to vehicle damage to the protective dune vegetation. Informal camp sites lack toilet facilities and have no rubbish disposal facilities. However the station does collect a camping fee for these sites. Usually camping is occurring within CALM's 40 m coast strip in poorly vegetated, fragile modern foredunes. Loss of vegetation, track damage and sediment 'blowouts' have occurred due to uncontrolled camping along the Warroora Station coastline. There are, however, a number of rocky headlands in the vicinity which would be environmentally stable as alternative camping sites.

Red Bluff is renowned for having one of the best surf breaks in the world, and attracts a constant flow of visitors. Red Bluff camp site can accommodate approximately 160 people. Red Bluff camp site conducts effective management control of a dispersed camp site that is situated on a stable and vegetated compacted red sand sheet (Figure 4-1-B). It may be argued that having such a dispersed camp site spreads the environmental degradation, however at present the soil and vegetation between camp sites is in good condition. Red Bluff also operates 17 long drop compost toilets which operate efficiently. Shallow rubbish disposal is the major anthropogenic impact that was identified at Red Bluff and occurs approximately 200 m north of the camp site (see Figure 4-3-A). On the day this photograph was taken (June, 2003) strong winds were blowing some of the shallowly disposed rubbish out of the pits into the surrounding vegetation. This is a noticeable failing in the camp site which is otherwise litter free.

Gnaraloo Station's Three Mile Camp has also been developed adjacent to a world class surfing break. The camp site can accommodate a maximum of 250 people. Three Mile Camp has a residential caretaker who aims to conserve the vegetation within and adjacent to the camp site. Despite this, the effects of camping have caused a major red sediment 'blowout' (Figure 4-1-A). Camping also continues only a few metres away from parabolic dunes. Figure 4-1-C depicts a large active parabolic dune immediately adjacent to 'formal' camping in a fragile dune system which is being reworked during windy conditions (note the blue sky appears white due to a mass of air born sand grains). However, the majority of the camping is occurring on stable and compacted red sediment, adjacent to a low cliff coast, that is reasonably resilient to campsite pressures provided appropriate management is exercised.

Gnaraloo Station offers a number of self contained chalets and a fishing shack (containing 25 beds) which are situated adjacent to the Gnaraloo Homestead (Figure 4-1-E and 4-1-F). Many of these chalets remain a long term unfinished project and detract from the visual serenity of the area. These chalets are located on a geologically optimum position. Their substrate is stable and their impact is away from the unstable coastal dunes. If future development is to occur, it should be by extending/completing the existing chalet complex.

The coastal access track in the northern sector of Gnaraloo Station between Cape

Farquar and Amherst Point has been closed for some time. The Station operator reported that approximately 50 people pass through the locked gate annually. This is a small proportion of the number of vehicles that access the Ningaloo Coast. The lack of anthropogenic impact between the locked gate sector is apparent in that there are very few tracks (no high risk areas) and very little environmental degradation. Active turtle nesting sites were also apparent. Of environmental interest was the abundance of yellow ghost crabs - *Ocypode convexa* present only in abundance between the locked gates where few vehicles were able to disturb their habitat. This species of crab has been identified as an indicator of human impact on beaches (Wolcott and Wolcott, 1984; Barros, 2000). It has been shown that track development near the beaches where crabs live, affects the exchange and supply of sand to the dune system and can interfere with the movement of many animals, such as ghost crabs (Barros, 2000). Refer to Appendix 3 for a detailed description of the crab sightings.

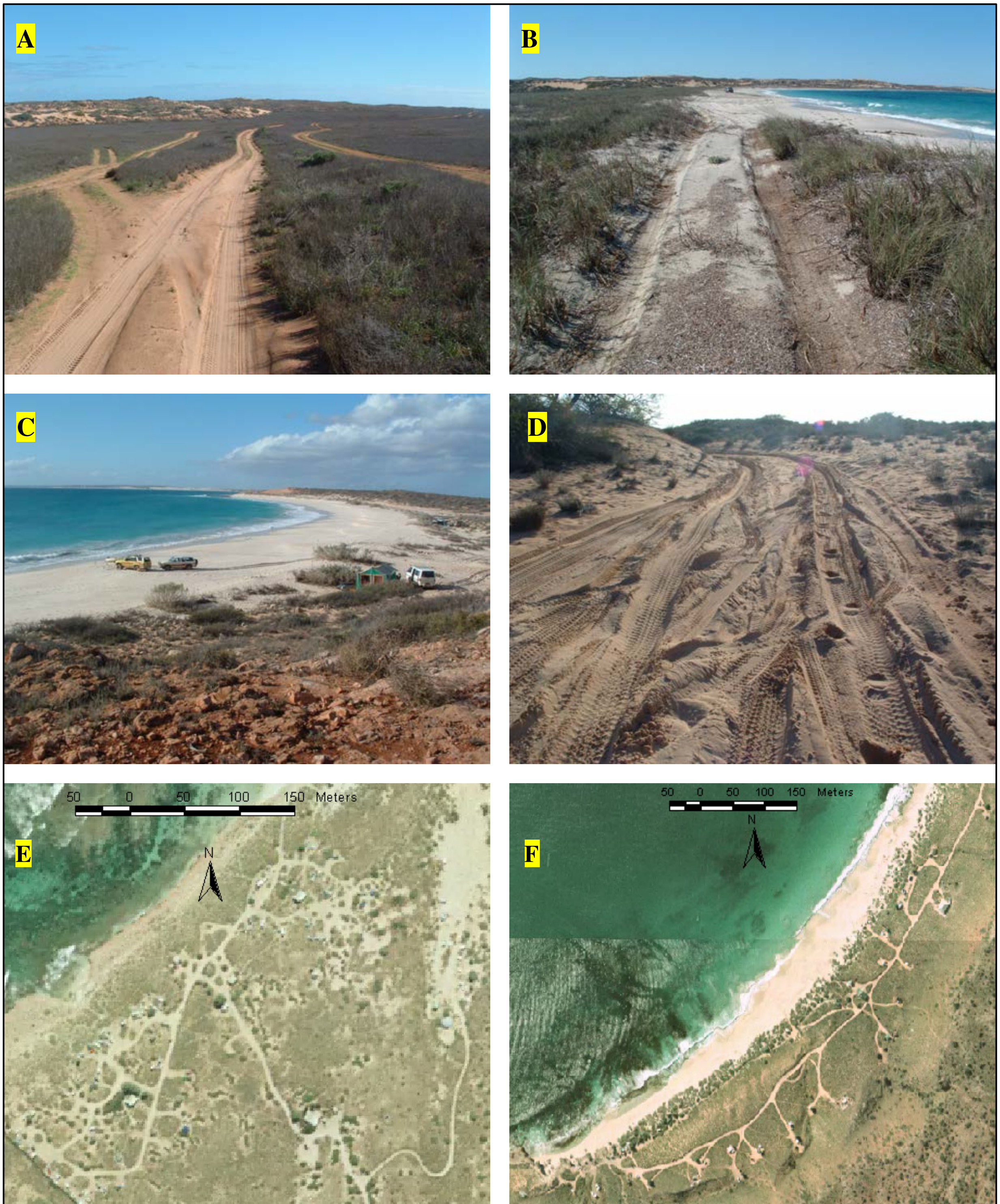
4.2 Ningaloo Region (Area X)

Being located at the southern extremity of the Cape Range National Park and encompassing the popular four wheel drive track that links Coral Bay to Yardie Creek significantly increases tourist visitation and recreational use on Ningaloo Station. Ningaloo Station boasts idyllic sheltered white sandy beaches that make it a popular camping location and a preferred site for future tourism development. Situated in Area X are a number of camp sites which are managed by Ningaloo Station. There are no toilet facilities, however rubbish is collected from designated pick up points on a regular basis. Within Area X is the Jane Bay camp site, which is situated on a saline flat. Loss of salt tolerant vegetation has occurred as a result of the Jane Bay camp site. Access tracks have proliferated around the camp sites and also on the ‘boggy’ saline flat terrain. The camp site near Jane Bay is reasonably resilient to camping pressures, provided station management ensures maintenance of minimum levels of vegetation, even though the camp site is situated behind fragile dunes. A major access track has been carved into the fragile dunes running from the camp site to the water’s edge. This track extends along the beach through modern foredunes and deflation basins and is used extensively for fishing and other recreational activities. It runs across some of the most fragile dune systems (Figure 4-2-B) along the coast and also through a turtle nesting site. Impacts created by this track are of major environmental concern.

A disused rubbish disposal site only a few metres from the pristine waters of Ningaloo located behind the homestead is another anthropogenic environmental impact visible in Area X (4-3-C). The rusted metals, broken glass and other debris are not only unsightly but also potentially hazardous to fauna and humans.

A. Three Mile Camp. **B.** Red Bluff Camp. **C.** Three Mile Camp **D.** An informal camp site on Warroora Station's southern boundary. **E. & F.** Gnaraloo Cabins (many of which are a long term unfinished project).

Figure 4-1. Examples of tourist nodes on the coast adjacent to Ningaloo Reef.



A. Proliferation of tracks on Ningaloo Station (Area X). **B.** Access track passing through turtle nesting area and degrading fragile vegetation on Ningaloo Station (Area X). **C.** Active beach tracks on Warroora Station (Area Y). **D.** Access track development through a parabolic dune on Warroora Station (Area Y). **E.** Aerial photograph of Three Mile Camp on Gnaraloo Station (Area Y).**F.** Aerial photograph of Red Bluff camp site on Quobba Station (Area Y).

Figure 4-2. Examples of access tracks in Areas X and Y on the coast adjacent to Ningaloo Reef.

A. Rubbish tip near Red Bluff camp site (Area Y: 750170,7341777). **B.** Sheep degrading the fragile dune vegetation on Warroora Station (Area Y: 077967, 7393859). **C.** Disused scrap metal rubbish tip on the shores of Ningaloo Reef on Ningaloo Station (Area X: 0774624, 7487718).

Figure 4-3. Anthropogenic impacts on the coastal plain adjacent to Ningaloo Reef.

5. COASTAL GEOMORPHOLOGY

The coastal geomorphology adjacent to Ningaloo Reef is highly variable, ranging from sandy beaches in the north to rugged cliffs in the south. Present day reef processes have largely determined the sediment supply to the coast, thus influencing the coastal morphology. Sea-level variations and climatic changes are also expressed in variations in landform development along the coast. All localities mentioned are identified in Figure 5-1.

5.1 Ningaloo Reef Structure and Evolution

The Ningaloo Reef has been the dominant control of sedimentation in the Holocene. The 290 km long segmented fringing reef forms a partial barrier of small continuous sections, causing the development of a distinctive lagoonal current pattern (Sanderson, 2002). The reef is a broad coral flat that is up to 150 m wide which out crops extensively, close to mean low water spring tide with the reef crest being emergent for 10% of the year (Hearn and Parker, 1988; Sanderson, 2000). The reef micro-topography shows a well-developed spur and groove morphology present on most outer slopes, with complex multiple developments of spur and groove also present (Collins, 2002). The landward lagoon ranges in width from 20 m to 6 km.

Collins et al. (2002) described and dated the development of the Ningaloo Reef based on data obtained from seismic lines and cores from both the modern reef and from the Last Interglacial Reef in the Tantabiddi area (see Figure 1-2). The Tantabiddi II core intersected Pleistocene reef below a disconformity at 18 m below sea-level and continued for 11 m. The top of this unit had a U series date of 115 ka BP and the base 119 ka BP. These dates suggest that the reef grew towards the end of the Last Interglacial high stand, later than most of the interglacial reefs that comprise the emergent terraces (Collins et al., 2002). It was found that the modern/Holocene reef has a thickness of 18 m; the base recording a U series age of 7.57 ka BP and being composed of relatively homogeneous robust coral framestone often bound by encrusting coralline algae (Collins et al., 2002).

5.2 Coastal Geomorphology

Much of the coast adjacent to Ningaloo Reef alternates between low limestone cliffs and sandy beaches. D.A. Lord and Associates (2000) investigated the coastal geomorphology between Carnarvon in the south to Sandy Point in the north, and divided the coast into 4 broad sub-regions on the basis of coastal geomorphology (Figure 5-1):

Delta Coast – Carnarvon to Miaboolya

Dune Coast – Miaboolya to Point Quobba

Cliff Coast – Point Quobba to Three Mile Camp

Dune and Cuspate Spit Coast – Three Mile Camp to Winderabandi Point

<u>Delta Coast</u> is exhibited between Carnarvon and Miaboolya Beach and is characterised by mangroves, tidal inlets and salt flats and was formed under influence of the Gascoyne River.

<u>Dune Coast</u> between Miaboolya and Point Quobba is a sedimentary coast and has largely formed under the influence of contemporary coastal processes. Along the southern section of this geomorphic sub-region, a series of shore-parallel beach ridges

are observed, and salt flats back these ridges. Towards the north, the beach ridge complex gives way to a series of mainly vegetated parabolic dunes; these dunes begin behind the beach ridge plain and extend northwards to Point Quobba (D.A. Lord and Associates, 2000).

Cliff Coast extends from Point Quobba to Three Mile Camp and is largely composed of low limestone cliffs with rocky shores and occasional pocket beaches.

Dune and Cuspate Spit Coast extends from Three Mile Camp to the north of Winderabandi Point. It is characterised by the presence of the Ningaloo Reef offshore and by the development of several coastal dune formations. A series of cuspate forelands have developed in the lee of the Ningaloo Reef due to the effects of wave sheltering and circulation patterns within the lagoon (Sanderson, 1997).

5.3 Terrestrial Geomorphology

Area X is situated within the Dune and Cuspate Spit Coast region. Area Y can be classified as a cliff coast that gradationally becomes a dune and cuspate spit coast from Three Mile Camp northwards. Sea-level variation coupled with lagoonal circulation and wind and wave actions have been the dominant coastal evolutionary processes.

This chapter is intended to be read in conjunction with the supporting digital maps or hard copy maps. For the purpose of maintaining lucid hard copy mapping detail, it was necessary to print Area Y in two hard copy maps (Area Y– North and Area Y – South). However the corresponding GIS data relating to Area Y is in one component. All three hard copy maps are at a scale of 1:35 000, however, digital maps can be accurately viewed from any scale to 1:3000.

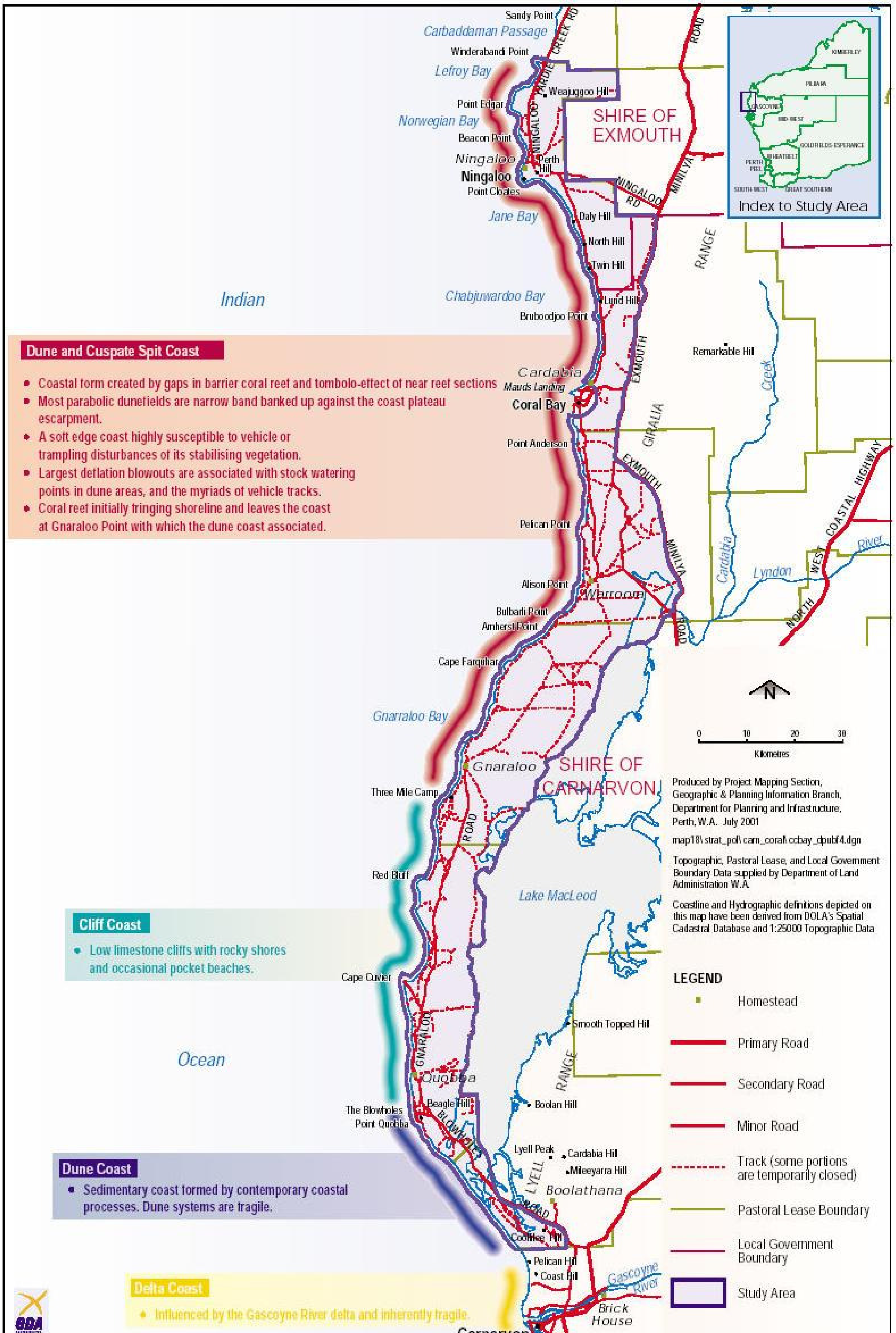


Figure 5-1. Coastal Geomorphology between Carnarvon and Sandy Point (after Shire of Carnarvon, 2001).

5.3.1 Ningaloo Region (Area X)

Area X is characterised by a limestone hinterland, including the initial emergence of the Cape Range Terraces, adjacent to: a dominant headland in the north (Point Cloates to the northern extremity of the mapped area), a central sandy active beach bay (Jane Bay) flanked by large parabolic dunes, a low lying rocky limestone coast flanked by parabolic dunes in the south (Figure 5-2). The large head land (Point Cloates) has been modified by the development of large parabolic dunes prograding from the south and is composed of a low lying beach ridge plain and parabolic dunes (maximum height of approximately 30 m).

The largest aerial component of Area X is the longitudinal dunes and sand plain. The iron oxides derived from this unit have stained the majority of the early Holocene parabolic dune deposits via the reworking of sediment, giving the older parabolic dunes a pale orange/brown colouration. The Tantabiddi Terrace, a paleo-reef lagoonal limestone, is covered by a variable thickness (0.5 m to 6 m) of red colluvial soils and unconsolidated sands. Most of this material has been derived from erosion of the extensive longitudinal dunes and sand plain to the east. The Tantabiddi Terrace displays an almost completely flat topography, with occasional relic-dune ridges.

Area X includes the southern extent of Cape Range, which rises to almost 50 m and consists of terraced limestone. The range decreases in elevation southward and has no surface expression to the east of Ningaloo Station. The terraces do not expose reefal assemblages, however they are comprosed of a calcretised skeletal grainstone (Figure 5-2-F) which typically overlies the older reef complexes (Figure 2-1). Hence the terraces have been mapped according to geomorphology and stratigraphic relationships, as well as geology. Figure 5-3 depicts the relationship between major geomorphic units situated in the north of Area X.

Jane Bay is a moderately deep bay with predominantly sandy shores (a rock pavement shoreline exists to the south of the bay). Typically, active sandy beaches are flanked by a narrow modern foredune (Figure 5-2-C). Parabolic dunes are located along the entire coast of Area X (Figure 5-2-E). The parabolic dunes begin as a narrow strip backed up on a low limestone cliff (Figure 5-2-A) in the south of Area X, and increase in height and width towards Jane Bay where they accumulate in thick deposits. The overlapping build-up of parabolic dunes at this locality is due to the east-west coastal orientation. The dominant prevailing wind direction is south-north, which directs sediment on shore. Deflation basins are often located between large parabolic dunes in Area X (Figure 5-2-D). These are abundant on the headland north of Point Cloates.

Saline flats occupy topographical lows in the headland of Area X and have a planar surface. They represent former outwash or inflow basins that were barred off by Holocene dunes. Also located on the headland, north of Ningaloo Homestead, is a beach ridge plain (Figure 5-4). These beach ridges are typically 1.5 m high with little variation and < 2 m between ridge and swale.

A. Low lying Bundera Limestone cliff coast (typical of the southern third of Area X). Vegetated parabolic dunes behind the cliff have been rubified.

B. Bundera Limestone cliff face displaying oblique foresets and uniform lamination.

C. Typical modern foredune (located at Jane Bay). Note the sparse vegetation.

D. Typical deflation basin (located at Jane Bay) Note the lithified dune core in the background.

E. Active parabolic dune in the south of Area X. Note the lush green grass due to recent rain.

F. Foresets (dipping at 32º W) in calcretised skeletal aeolian grainstone that caps the Milyering Terrace.

Figure 5-2. Photographs of geomorphological features in Area X.

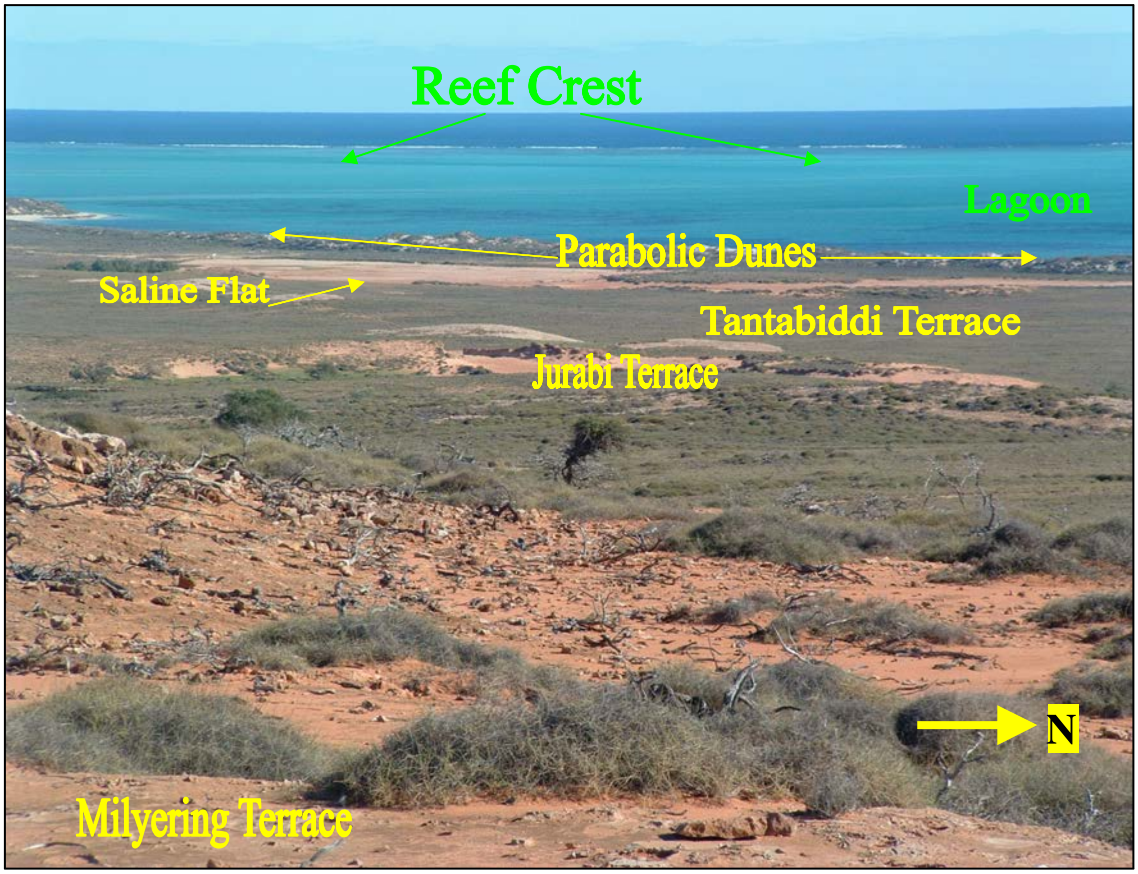


Figure 5-3. Photograph of Ningaloo area depicting geomorphic relationships of north Area X. The photograph was shot from the Milyering Terrace facing west.

Figure 5-4. Panoramic photo of the beach ridge plain located north-west of Ningaloo Homestead, north of Point Cloates. Showing near-flat topography and high vegetation cover. This area currently receives low use.

5.3.2 Gnaraloo Region (Area Y)

Area Y is characterised by the variably calcretised Trealla Limestone coastal scarp that is typically present landward of the coastal zone (Figure 5-5-C). This scarp is backed by a plateau which extends eastward beyond the mapped area and is overlain by red longitudinal desert dunes (Figure 5-6-F). The coast of the southern quarter of Area Y is predominantly Tertiary Trealla Limestone that is typically 2 – 20 m high (Figure 5-5-A), flanked by parabolic dunes (Figure 5-5-D) that within a short distance give way to older red longitudinal dunes. In the central sector of Area Y the Trealla Limestone plateau is located within 2 km of the shoreline, a distance that increases as it progresses northwards. The plateau between Cape Farquar and Alison Point is deeply incised by creeks which run westward to the sea from the Giralia Range (Figure 5-6-A).

North of Three Mile Camp, beach ridges are the main lithology adjacent to the shoreline and these are typically backed by recent parabolic dunes. Bare mobile parabolic dunes are present throughout this area and are mostly associated with stock watering points. Many sectors of Area Y lack any Holocene deposition due to the erosive nature of the coast in the southern end of Area Y.

Present along the coast are a number of the barred rivers/creeks. The bars are composed of quartz/skeletal grainstone, with repeated pebble horizons (Figure 5-6-D). The pebbly rudstone layers in this unit contain 30 cm long clasts derived from the Giralia Range, and are indicative of high energy events such as floods. Therefore occasional coarse sediment transport moves seaward, and normal daily sediment transport is landward, accreting sediment to the sand bar. Figure 5-6-C illustrates a series of beach cusps carved into the active sandy beach adjacent to the barred creek. Cusps are indicative of the Holocene sediment transport direction, and nearshore circulation currents. The presence of rocky bars located in the throat of barred coasts represents an earlier phase of estuarine evolution and shoreline development.

The cliff coast in Area Y is composed of three distinct lithologies: Bundera Limestone, Trealla Limestone (Figure 5-5-A) and Tantabiddi Rudstone/Reef (Figure 5-5-B). The Tantabiddi Last Interglacial Reef deposit is exposed at a number of localities along the coast of area Y (e.g. Red Bluff and Three Mile Camp). The unit is in near-pristine condition at many of these localities and has preserved world class coral reef assemblages. The transition between cliff coast and dune coast ranges from gradational to sharp (Figure 5-5-E) depending on the pre-existing topography.

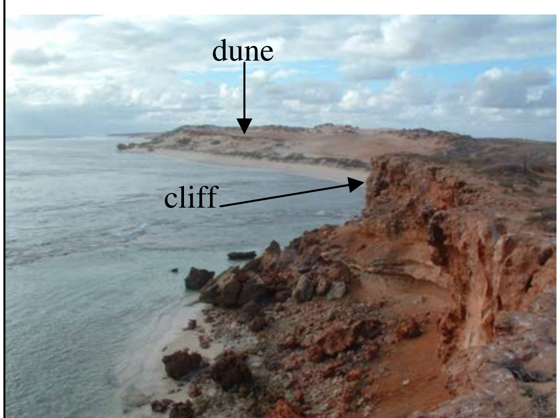
Intertidal pavements are present at numerous localities along the coast. Lithologies of these are hard to determine (due to heavy algal encrustation) without thin section analysis, however they are most likely Bundera Limestone (Figure 5-6-E) and Trealla Limestone.

Refer to appendix four to view thin section analysis data of the main lithologies present in Areas X and Y.

A. Tertiary Trealla Limestone cliff coast, typical of the coast between Red Bluff and Three Mile Camp.

B. Last Interglacial Tantabiddi Reef cliff coast, photograph taken north of Red Bluff.

C. Trealla Limestone scarp and plateau typical of the southern half of Area Y (Red Bluff).



E. The immediate transition between cliff coast and dune coast (0779193, 7393683).

F. A typical beach ridge in front of a vegetated parabolic dune on a low lying cliff coast. Red Bluff is in the background.

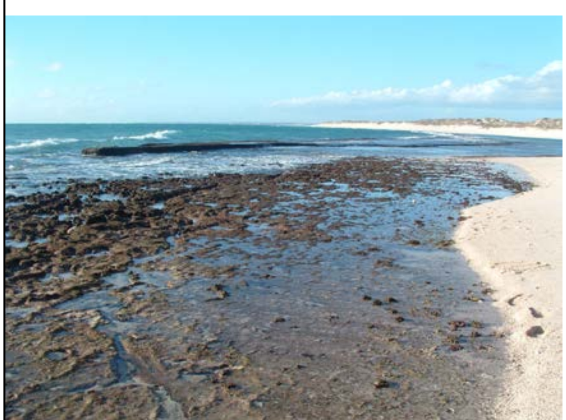
Figure 5-5. Photographs of geomorphological features in Area Y.

A. Permanent water body in a small estuary, north of Amherst Point.

B. Large active parabolic dune, located south of Three Mile Camp. Note the recently constructed protective fence.

C. A series of beach cusps carved into the active beach , near Bulbari Point.

D. An estuarine lithified bar deposit located where the estuary meets the ocean, near Bulbari Point.



E. Behind the intertidal pavement is the reef crest of the living Ningaloo Reef , Amherst Point area.

F. Calcretised surface of the Trealla Limestone, covered with a thin red sediment veneer sourced from the longitudinal dunes.

Figure 5-6. Photographs of geomorphological features in Area Y.

6. LAND SYSTEM UNITS

Land system units are delineated by geological boundaries, and then further defined by the unit's substrate capacity and land use characteristics. They are therefore interchangeable with geological/geomorphological units, but include additional land management information such as, soil type, physical characteristics, current land use and vegetation cover. Comments are from field observations. Table 6-1 describes the characteristics of the 23 land system units present in Areas X and Y.

Table 6-1. Geological and land use features of the 23 units present in Areas X and Y adjacent to the Ningaloo Reef (in order of increasing substrate capacity).

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Active Beach (sandy) (Qsa)	1	Variable thickness (2 to 10 m) and width (2 to 15 m). Predominantly composed of medium to coarse calcareous sand. Occasional storm deposits.	Nil.	Unconsolidated sands. Active wind and wave erosion. Highly variable width. Unit is reworked by tidal and wave action (predominantly depositional/ replenishing system). Periodically eroded by storms.	Little vehicle use. Areas of coastal access have high vehicle use e.g. where inland routes are either non-existent or blocked.	Turtle nesting sites are present on Ningaloo, Gnaraloo and Warroora Stations.
Modern Foredune (Qsf)	1	Single linear dune parallel to coast with high-slope dune face. Variable height (1 to 10 m) and width (1 to 20 m). Adjacent to the active beach (sandy).	Very sparse to nil vegetation (hummocky grassland).	Unconsolidated calcareous sand. Denudation primarily caused by camping and live stock damage.	Commonly eroded in high use zones by access to the beach or camping sites situated in the foredune itself.	A coast that faces the prevailing wind during Tropical Cyclones typically develops high foredunes.

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Beach Ridges (Un-vegetated) (QsrU)	1	Low to medium gradient linear dunes. Commonly forming beach ridge plains. Dunes range in height (0.5 to 4 m) and width (1 to 8 m). Mobile unlithified calcareous sand.	Nil.	Unconsolidated calcareous sand. Denudation primarily caused by live stock damage.	Very little to no vehicle access. Private access is restricted in the northern section of Gnaraloo Station (via a locked gate). Significant stock damage.	Vegetated beach ridges have been mapped as a separate unit (Qsr).
Un-vegetated Red Sediment/ Sand Plain (Blowout) (QsbB)	1	Active blowouts in sand plain. Composed of unlithified rubified sand.	Nil.	Blowouts form predominantly as a direct result of loss of vegetation which is caused by access tracks and live stock land use. Also formed due to fire associated vegetation loss and severe winds.	Many are intersected by access tracks.	The majority of blowouts are initiated by access tracks or are associated with livestock watering points. Most are prograding north-easterly in the direction of prevailing wind.

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Parabolic Dunes (Active) (QspA)	1	Highly variable height (1 to 30 m) and width (1 to 50 m). High marginal slopes and unstable sediment.	Nil to very little.	Currently prograding. Can affect adjacent units (partially covering them).	None to very little. A small number of dunes are utilised for sand boarding.	High gradient active parabolic dunes are utilised by sand boarders which prevents stabilisation.
Beach (rocky) (QsaR)	2	Variable thickness(0.5 to 7 m) and width (1 to 15 m). Low to medium angle beach face. Predominantly composed of medium to coarse calcareous sand but with significant rock out crop. Includes shoreline, intertidal rock pavements. Rock units = Bundera Limestone and Trealla Limestone.	Nil.	Active wind and wave erosion. Highly variable thickness. Unit is reworked by tidal and wave action (predominantly depositional/ replenishing system), subject to periodic storm erosion.	Predominantly little to no vehicle use. Areas of coastal access have high vehicle use e.g. where inland routes are either non-existent or blocked.	A rocky beach was distinguished from the active beach unit as being composed predominantly of limestone outcrop as opposed to unconsolidated sand.

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Beach Ridge (Qsr)	2	Low to medium gradient linear dunes. Commonly forming beach ridge plains. Dunes range in height (0.5 to 4 m) and width (1 to 8 m). Prograded from highstand paleo-shoreline or seaward face of parabolic dunes towards the modern shoreline.	Low to medium vegetation cover (grassland and scrubland).	Unconsolidated calcareous sand. Predominantly low sloped ridges.	Utilised for substantial access and camping sites.	Large denuded/un vegetated areas have been mapped as a separate unit (QsrU). In general, the beach ridges in Area Y were larger than those mapped in Area X.
Saline Flat (Ql)	2	Low lying, highly saline (gypsiferous) flats. Composed of marine sands and overlying saline soils and algal crusts. Marine metahaline shell assemblages sometimes present. Variable thickness (0 to 3 m) over pre-existing topography.	Sparse salt tolerant vegetation cover.	Becomes muddy very quickly after rain. Can flood during more extreme rain events (drainage is directed to the lowest topography).	Heavily utilised for access and a camping site on Ningaloo Station.	Many saline flats contain stock watering sites.

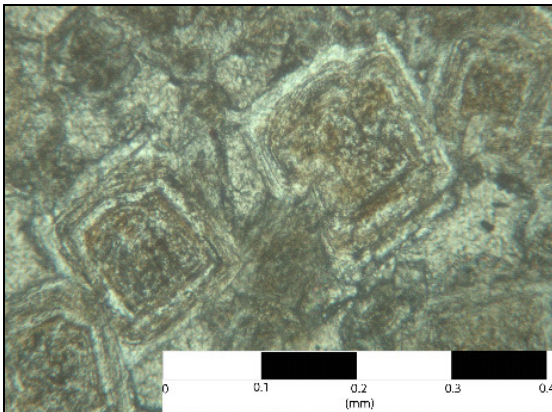
UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Parabolic Dunes (Qsdp)	2	Highly variable height (1 to 30 m) and width (up to 50 m). High marginal slopes and unstable sediment.	Sparse to densely vegetated depending on age. In some areas vegetation has been fire damaged.	Have been stable for considerable time. Dune cores are frequently partially consolidated.	Low to medium use due to the steep slopes of the dune faces.	This unit is the major geomorphic feature of the immediate coast on Ningaloo Station. Some dunes have only a sparse cover of buffel grass due to fire damage and are unstable.
Relict Foredune (QsfR)	2	Variable height (2 to 10 m) and width (2 to 20 m).	Medium to densely vegetated.	Linear dunes running parallel to coast line.	Little use.	Occur in localised pockets.
Cuspate Foreland (Qsc)	2	Cusp shaped coastal sediment accumulation.	Sparse (coastal heath).	Low relief and cuspate form.	Often sought after for recreational purposes. Minor access tracks.	Cuspate forelands develop as nodes of sedimentation.

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Red Sand Sheet/sand plain (Qsb)	3	Compacted fine grained unconsolidated red sediment. Thickness varies (0.5 to 6 m).	Moderate vegetation.	Derived from erosion of (red) Longitudinal Dunes and Sand Plain.	Due to its relatively stable and flat topography this unit is extensively used for camp sites (e.g. at Red Bluff camp site and Three Mile Camp site).	If managed effectively, camp sites on this unit are able to withstand anthropogenic impacts. However if environmental management is inadequate degradation will occur (in the form of loss of vegetation and destabilisation of the compacted sediment) resulting in 'blowouts'.
Longitudinal Dunes and Sand Plain (QbeS)	3	High marginal slopes. Predominantly composed of a variable mix of quartz and carbonate (the closer to the coast, the higher the carbonate content). Rubified grains.	Sparsely to densely vegetated.	Cover of unconsolidated material has high potential to blow out especially where vegetation cover has been burnt.	Network of access ways ranging from sand tracks to sealed roads.	This unit is very extensive across the Gascoyne region. The unit extends from the base of Exmouth Gulf to Carnarvon. See Figure 6-1-C.

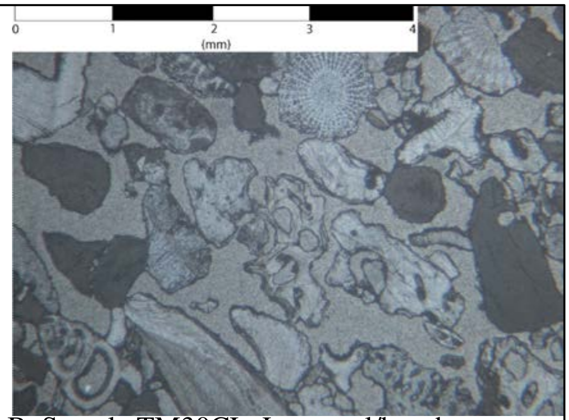
UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Tantabiddi Last Interglacial Reef (Qbtr)	3	Cliffs vary in height (1 to 7 m) beginning at modern day sea-level and vary in width (2 to 15 m). Composed of coral reef assemblage similar to that of the modern Ningaloo Reef.	Nil.	Located as raised reef along cliff coast.	No vehicle use. Minor pedestrian usage.	Fine example of a Last Interglacial Reef, much of it is in relatively pristine condition. Not previously recognised in this area. This unit is not visible in Area X.
Tantabiddi Terrace (Pbt)	3	Last Inter Glacial Limestone paleo reef/lagoon system formed over wave cut terrace. Overlain by 0.5 to 5 m of unconsolidated soils and calcareous sand (visible in trenches and quarries).	Low to high vegetation cover including small groves of Acacias.	A limestone pavement under laying a varying cover of unconsolidated soil and calcareous sand.	Main north-south access tracks (the Coral Bay to Yardie Creek major track) are located on this unit in Area X.	This unit is not visible in Area Y.
Deflation Basin (Qsd)	3	Variable width (2 to 50 m).	Medium vegetation cover.	Flat topography.	Little access use.	Large deflation basins on Ningaloo Station (Area X), East of Norwegian Bay. See Figure 6-1-D.

UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Bundera Limestone Outcrop (Qb) Also includes: (Qbe and Qbr)		Coastal and sand plain outcrops. Composed of consolidated limestone that is often highly calcretised. Forms both rock platforms and cliff/rocky coast. Cliffs vary in height (0.5 to 10 m). Provides rocky intertidal substrates and commonly forms the 'core' to headlands. Predominantly aeolian limestone however minor marine fossils are also present occasionally.	Nil to very little.	Occupies small areas.	The unit is utilised for access where tracks intersect it.	Outcrops are coastal cliffs, relic shorelines, or exposed paleo dune crests. See Appendix 1 for descriptions of the various components of Bundera Limestone. See Figure 6-1-F.
Calcrete (Czk)	4	Hard limestone with strong secondary carbonate cement.	Sparse	Forms discontinuous cover over Tertiary limestone and various other units.	Rarely utilised.	Developed as a surficial deposit over limestone topography.

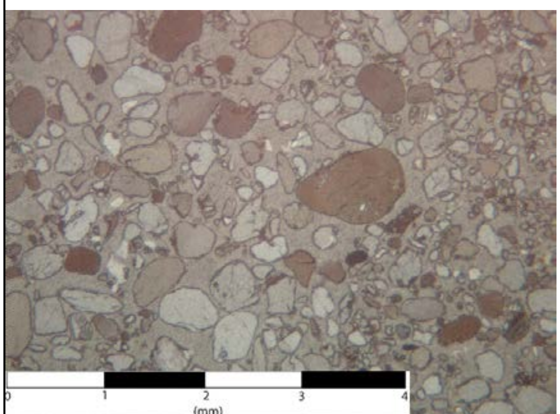
UNIT	SCI	DESCRIPTION	VEGETATION	CHARACTERISTICS	LAND USE	COMMENTS
Trealla Limestone (Tt)	5	Cliffs vary from 1 to 50 m in height. Variably calcretised. Yellow to cream coloured coarse crystalline Limestone.	Moderate vegetation cover.	Composed of hard limestone.	Minor access track use.	A stable substrate. Exposed only in Area Y.
Jurabi Member (Pbj)	5	Terraced rock outcrop. Variable height (ca 10 to 20 m),and width (20 to 100 m). Composed of well consolidated calcretised limestone.	Sparse grassland and sporadic scrubland cover.	An elevated rocky terrace that is parallel to the coast.	Very minor to no track access.	Stable, and also located at distance from the fragile coastal geomorphology. Exposed only in Area X.
Milyering Member (Pxm) and Muiron Member (Pxn)	5	Limestone rock outcrop that continues north to form part of Cape Range. Height ca 100m. Composed of consolidated sandy calcretised limestone.	Minor vegetation cover due to limited soil supply.	Very steep and gullied topography.	Very minor to no track access.	Could be potentially utilised as a view point on Ningaloo Station as its high elevation creates a scenic lookout. Exposed only in Area X.



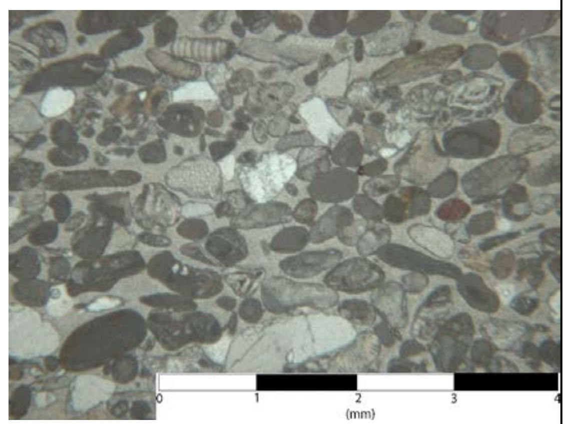
A. Sample RB41CL. Rhombic shaped dolomite grains with strong zonation.



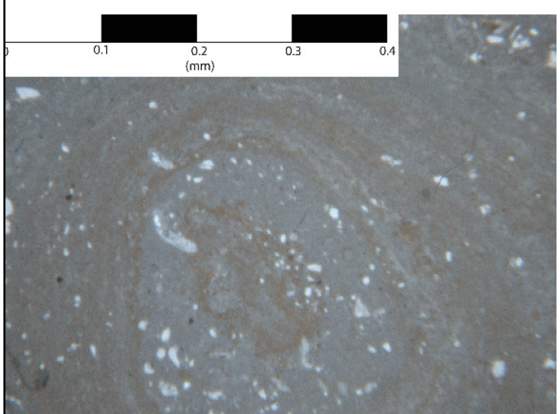
B. Sample TM30CL. Lagoonal/beach mixed sand deposit.



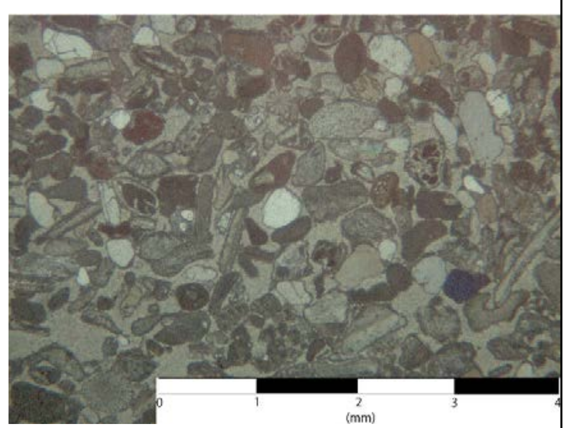
C. Sample 46CL. Red clays have coated the quartz grains giving the unit (longitudinal desert dunes) a rich red colour.



D. Sample DB56CL. Deflation basin lithified sediment. Mixed skeletal grain assemblage.



E. Sample PC1CL. Concentric iron oxide stained rims (pisolite structure) on weathered surface of Trealla Limestone.



F. Sample RB40CL. Bundera skeletal grainstone from a relict dune unit.

Figure 6-1. Thin section images of selected samples of the coastal units adjacent to Ningaloo Reef.. All photographs were taken under transmitted light and plain polarisation. To view petrographic descriptions of the above samples see Appendix 4.

7. QUATERNARY COASTAL EVOLUTION

The coastal evolution adjacent to Ningaloo Reef in Area X is vastly different to that of Area Y. This is primarily due to the effect of pre-existing topography and its interactions with Holocene deposition. Ningaloo Reef has also influenced the variations in coastal evolution via the disruption of sediment flow. In Area X the reef crest is wide, almost continuous and located 2 to 5 km offshore, whereas in Area Y the reef is narrower, closer to the shore and far less continuous.

The coast adjacent to Area X has developed during the Quaternary, predominantly in response to glacial sea-level changes. Last Interglacial and Plio-Pleistocene units formed the existing surface and initial topography for Holocene coastal evolution in response to a transgressive-regressive cycle of sea-level change in the Holocene. The pre-existing coastal topography adjacent to Area Y has predominantly developed during the Miocene epoch of the Tertiary period in the form of the Trealla Limestone. Plio-Pleistocene units have been deposited overlying this substrate. Holocene deposits occur west of the Trealla Limestone, however are absent where steep limestone cliffs abut the waters edge.

Table 7-1. Geological time chart showing the subdivisions of Cenozoic time.

Eon	Era	Period		Epoch	Millions of Years Ago
Phanerozoic	Cenozoic	Quaternary		Recent or Holocene	0.01
				Pleistocene	1.6
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.7
			Paleogene	Oligocene	36.6
				Eocene	57.8
				Paleocene	66

7.1 Miocene Coastal Evolution

Trealla Limestone is typically a cream coloured bioclastic packstone/grainstone, and is indicative of deposition in shallow, agitated waters; it represents the greatest extent of the Miocene transgression in the Carnarvon Basin (Denman and Van de Graaff, 1978). Part of the Trealla Limestone was probably deposited in a lagoonal environment, with intermittent emergence (Denman and Van de Graaff, 1978), and this facies appears to be present south of Gnaraloo Homestead. The foraminiferal faunas within the Trealla Limestone indicate a latest Early Miocene to Middle Miocene age (Denman and Van de Graaff, 1978).

7.2 Plio-Pleistocene Coastal Evolution

Plio-Pleistocene deposition adjacent to Ningaloo Reef is an analogue of the modern reefal deposition system, overprinted with glacial sea-level variations and tectonic uplift (Wyrwoll et al., 1992). Plio-Pleistocene units present in the two mapped areas are, in order of increasing age; un-vegetated red sediment/sand plain (a diachronous unit), longitudinal dunes and sand plain, Bundera Limestone (including Tantabiddi and Jurabi Terraces), Milyering and Muiron Sandstone Members.

Area Y exhibits coastal sectors containing well preserved Pleistocene stratigraphic evolution. Figure 7-1 is a block diagram of Red Bluff (located at the southern extent of Area Y). It depicts the Pleistocene deposition over the pre-existing Tertiary topography. A Pleistocene beach sequence is present on the western side of the Trealla Limestone cliff. This sequence consists of a steeply dipping (35º) skeletal grainstone, indicative of a former dune which overlies a thin reworked sandy rudstone, probably a beach/lagoonal deposit. These two units were deposited above Tantabiddi Member framestone, a Last Interglacial Reef member of the Bundera Limestone which is observed to overlie the Trealla Limestone. The framestone is largely composed of gravel sheets of plate corals and algae, typical of high energy depositional environments. Red longitudinal desert dunes of Pleistocene age cover the Trealla Limestone plateau.

7.2.1 Pleistocene Desert Dune Evolution

Pleistocene desert dunes (longitudinal dunes and sand plain) dominate the inland regions of the coastal plain and are an expression of significant climate change to more arid conditions. The dunes have a longitudinal form and have been rubified to varying degrees with colours ranging from medium brown to dark reddish brown. Two major areas of desert dunes have been identified in the region (Kendrick at al., 1991). The first region of dunes 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, plus well developed calcrete in some areas. They act as an important control on Quaternary geomorphological evolution of coastal regions, forming the barrier to Quaternary drowning. The second area is smaller in size, consisting of red siliceous dunes, with little pedological development, and is located on the north west of the peninsula, covering an area of approximately 25 km^2. Wyrwoll et al. (1992) obtained two thermoluminescence ages from the dune area north of the peninsular. Both ages (23.4±6.7 and 16±1.7 ka BP) are indicative of deposition during the Last Glacial Maximum. The dunes are evidence for aridity during this time (Wyrwoll et al., 1992).

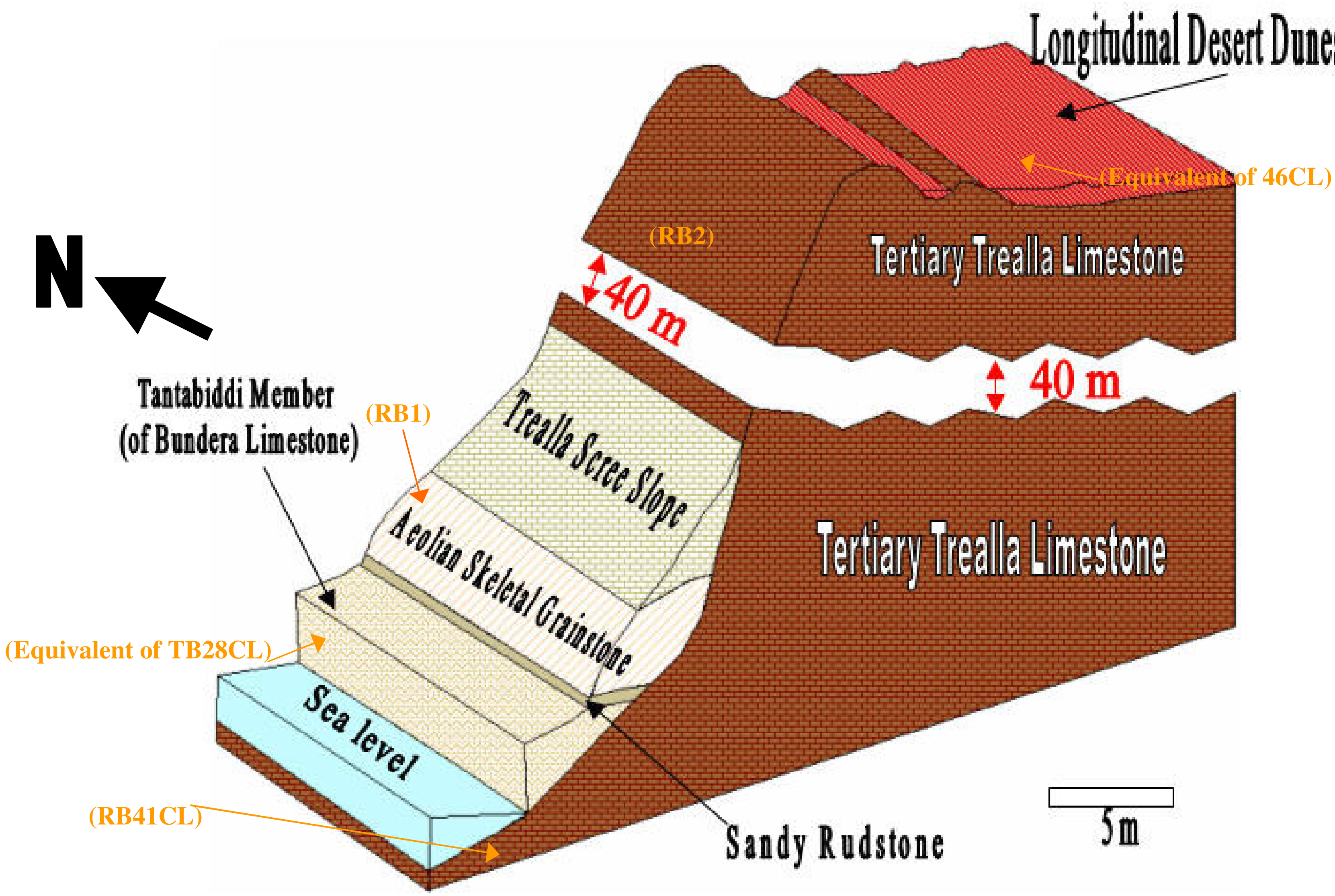


Figure 7-1. Geological cross section of Red Bluff illustrating the Plio-Pleistocene evolution overlying the pre existing topography (Trealla Limestone). The numbers in orange refer to rock samples described in thin section (see Appendix 4). No vertical exaggeration.

No dates have been obtained from the major dune field encompassing Areas X and Y. The dune field extends from the eastern extent of the study towards the coast, and at places it is immediately adjacent to the active beach (in Area Y). It is composed of variable proportions of quartz, carbonate and rubified clay size particles that have stained the quartz and carbonate grains (Figure 6-1-C). The carbonate content tends to increase with proximity to the coast. In general the desert dunes in Area Y have a lower carbonate content than those in Area X, and this can be attributed to the lack of recent carbonate deposition in Area Y. In Area X sediment derived from the red Pleistocene dunes overlies the Tantabiddi Terrace and extends west to the Holocene dune deposits. In Area Y the extensive red desert dune plain predominantly overlies the Trealla Limestone.

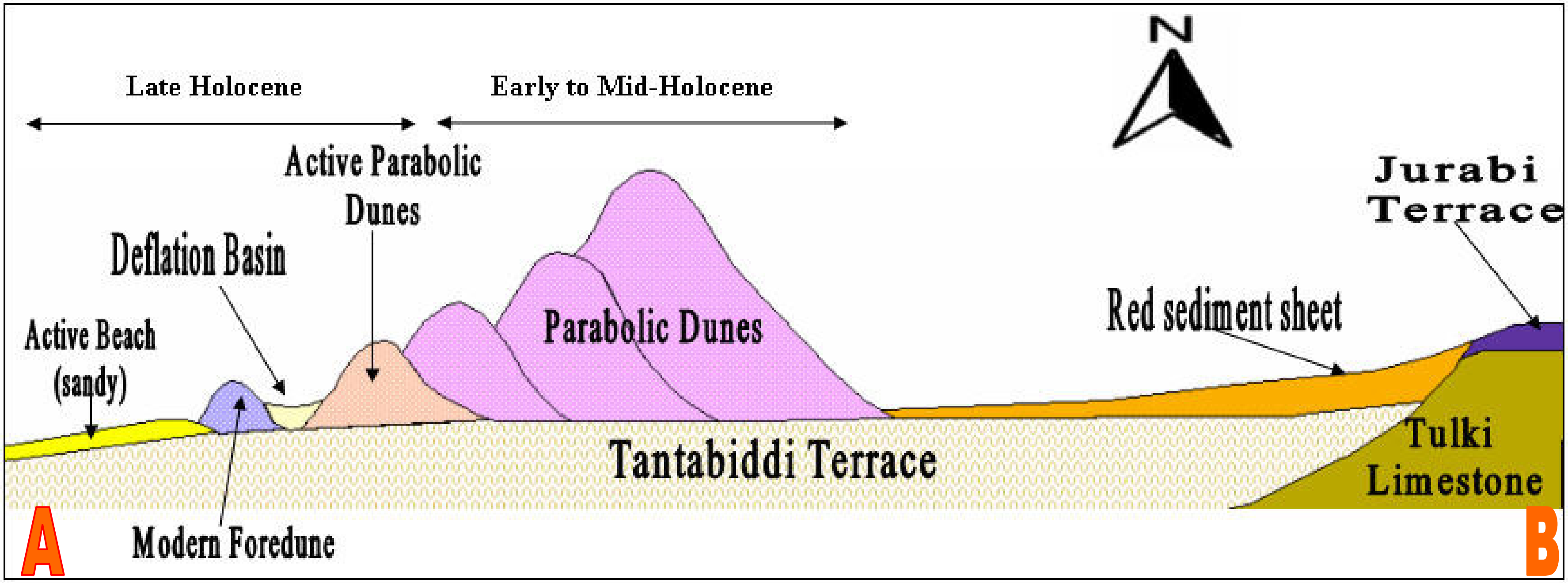
7.2.2 Cape Range Terrace Evolution

Van de Graaff et al. (1976) were the first to describe in detail the emergent terraces on the western flank of the Cape Range. These terraces provide a record of tectonic history, indicating their uplift and a range of sea-level changes. Van de Graaff et al. (1976) distinguished four erosional terraces - Tantabiddi, Jurabi, Milyering and Muiron. Each terrace is overlain by shallow marine and shoreline sediments and truncated seaward by an erosional scarp, forming the corresponding members (van de Graaff et al., 1976). The overlying unit on the Tantabiddi and Jurabi Terraces is the Bundera Calcarenite and the overlying unit on the Milyering and Murion terraces is the Exmouth Sandstone (Figure 2-1). The Tantabiddi Terrace has been dated (~125 ka BP), as it is the youngest member and has not been subjected to intensive recrystallisation as have been the older terraces. It is thought that the Jurabi Member is of Miocene to Pliocene age based on fossil evidence; *Carcharocles Megladon* teeth found here have a global distribution in the Miocene to Pliocene (Kendrick et al., 1991).

The Tantabiddi Member forms the basement of the coastal plain and the lagoon (Figure 7-2). It also forms the substrate of the modern Ningaloo Reef (Wyrwoll et al., 1992; Collins et al., 2002) therefore making it a dominant control on the Quaternary geology of the coastal plain adjacent to the Cape Range. Late Pleistocene and Holocene dunes overlie the terrace at the coastal margin. Kendrick et al. (1991) dated a Late Pleistocene intertidal beach/rock deposit at Pilgramunna Creek and obtained a date of 130±6 ka BP for transported coral from a beach rock unit in the landward side of the two dune units. The seaward unit was dated at 118±5 ka BP; this may be evidence for two discrete sea-level events during Oxygen Isotope Sub-stage 5e. Kendrick et al. (1991) also logged another section of the Tantabiddi Member at Bolman Hill, just north of Coral Bay, which showed a cross-bedded dune unit that gave a thermoluminescence age of 40.2±8.4 ka BP. This unit is thought to represent a sea-level event which did not reach present day level but was sufficiently high to be registered in the dune record. This may be evidence for a high sea-level later than the Oxygen Isotope Sub-stage 5e.

7.3 Holocene Coastal Evolution

The Holocene (≈10,000 ka BP to present) evolution of the coastal plain adjacent to Ningaloo Reef has been variable due to pre-existing topography. The coastal evolution adjacent to the northern sector of the reef (Area X and the northern half of Area Y) has



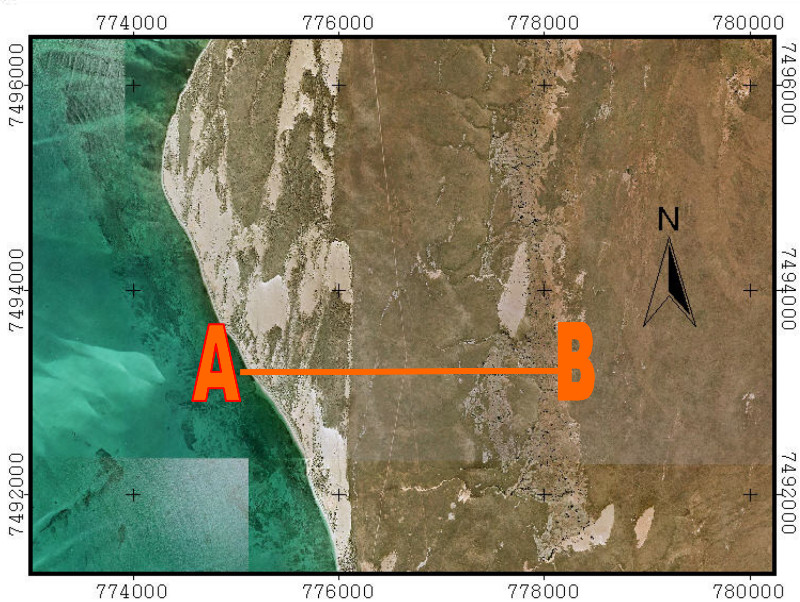


Figure 7-2. Cross section of the major units present adjacent to the Ningaloo Reef in Area X (not to scale). This example is based on an east-west section south of Beacon Point (Area X).

occurred in five main stages; shelf erosion and shore face retreat, transgressive deposits, highstand deposits, regressive deposits and modern beach and foredune development. Late Holocene sea-level variations resulted in the first four stages (Figures 7-3 and 7-4), and the last is a consequence of the modern sedimentary system (Blackwell, 2002). These stages of coastal evolution are not present in the southern half of Area Y due to the erosive nature of this cliff coast.

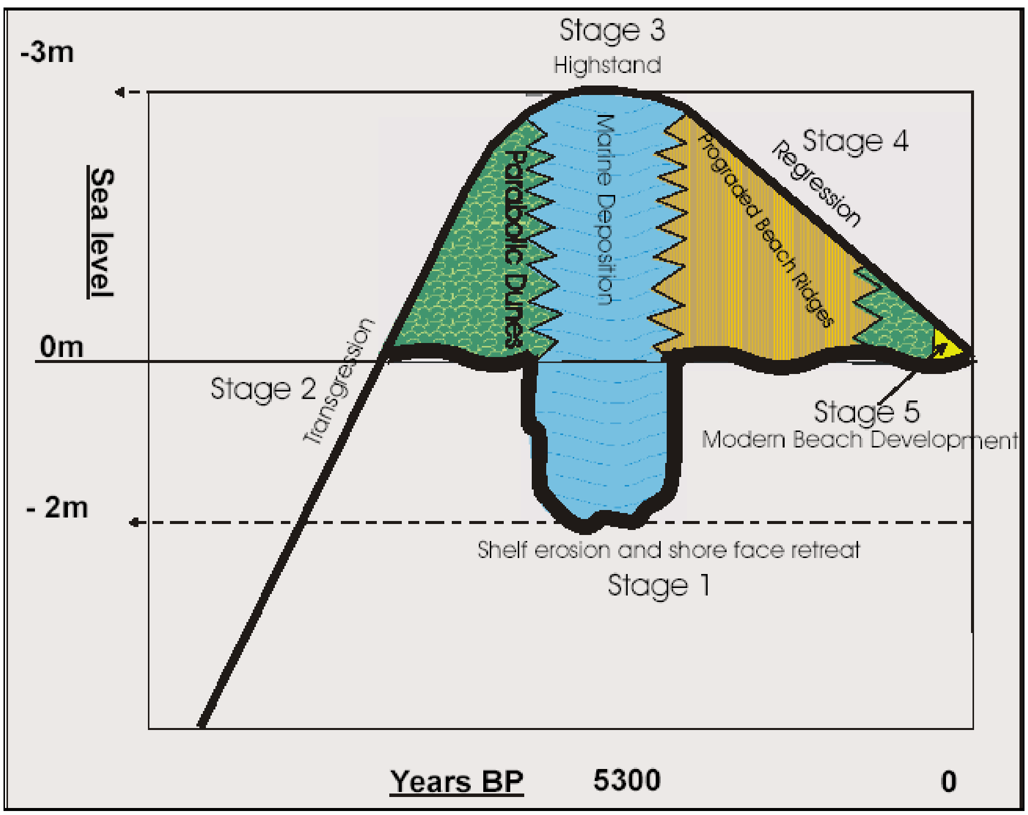


Figure 7-3. The Holocene sea-level relationship to major coastal units adjacent to Ningaloo Reef and the corresponding five Holocene coastal evolution stages. Note: this model only applies to Area X (after Blackwell, 2002).

7.3.1 Holocene Evolution Stage 1: shelf erosion and shore face retreat

Following the Last Glacial Maximum sea-level (-120 m) at 20 ka BP, sea-level rose and had reached the current level by approximately 6000 ka BP (Collins et al., 1993; Baker et al., 2001; Yokoyama et al., 2001). This period was characterised by shelf erosion and shoreface retreat which resulted in Holocene and pre-Holocene sediments being stripped from the Pleistocene shelf surface, remobilisation and landward transportation. The earliest record of onshore deposition is marine embayment fill, deposited in coastal depressions as the rising sea-level breached coastal barriers and flooded small inland basins such as the saline flat north-west of Ningaloo Homestead (Area X) and the two small saline flats adjacent to Gnaraloo Bay (Area Y).

7.3.2 Holocene Evolution Stage 2: transgressive deposits

Between 6000 ka BP and 5300 ka BP a highstand of 2 – 3 m occurred during the Late Holocene period. During this stage, the transgressive units presently adjacent to Ningaloo Reef were deposited (e.g. large parabolic dunes). Local marine deposition continued during this stage as sea-level rose and local depressions developed from intertidal bays into shallow marine embayments. The parabolic dunes that dominate much of the coast adjacent to Ningaloo Reef are the major expression of this stage (Figure 7-2). Deposition started when the transgression allowed sediment to inundate coastal lowlands and continued during the subsequent highstand. The present day parabolic dunes are not as well developed as the stage 2 transgressive parabolic dunes, hence sediment supply was higher than that available at present. The source of this sediment was from the continental shelf, both as pre-Holocene sediment, and

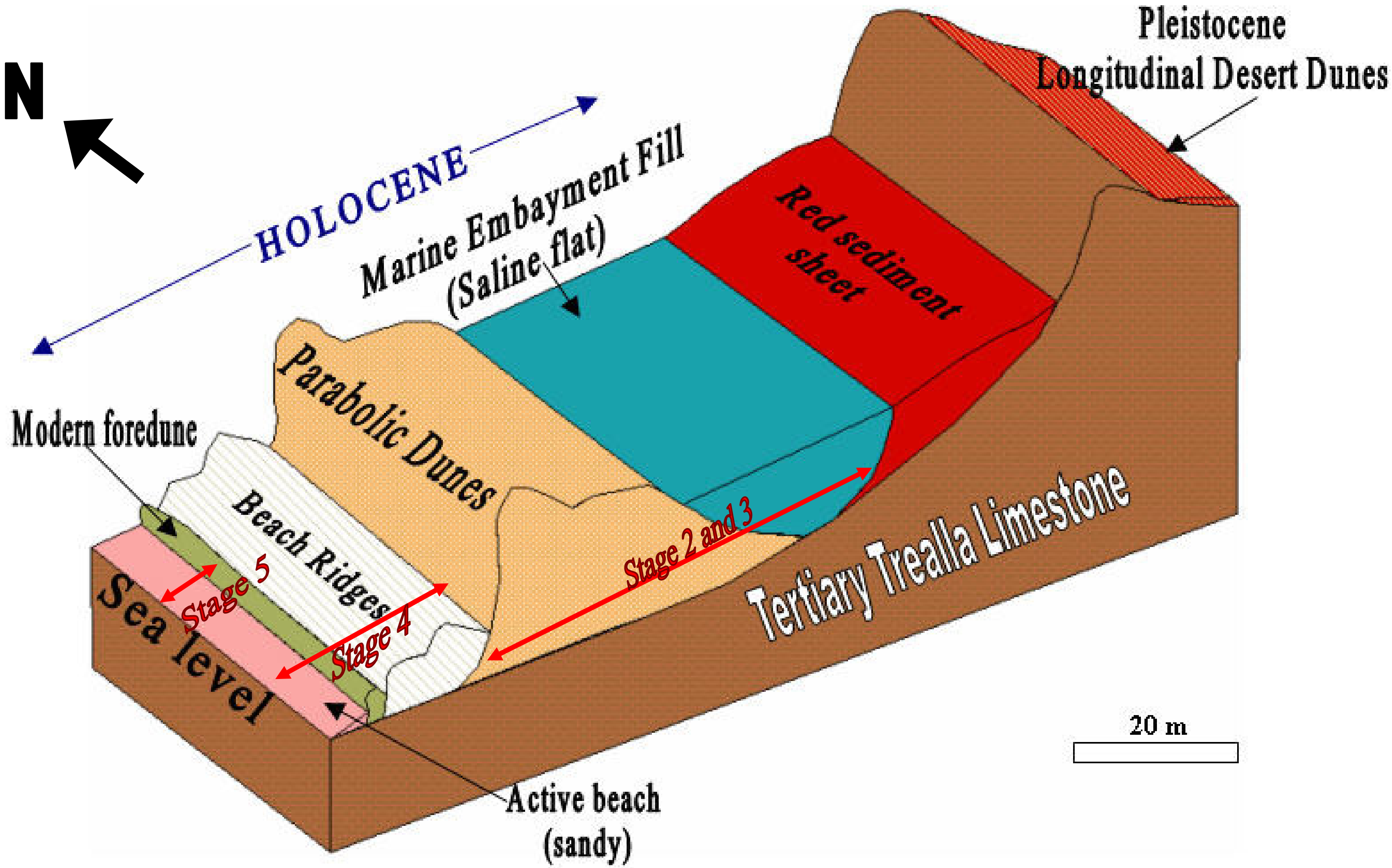


Figure 7-4. Geological cross section of the major units present adjacent to Ningaloo Reef. This example is based on an East-West section across Gnaraloo Bay (Area Y) and typifies prograded coastal stratigraphy in both Areas. No vertical exaggeration has been used.

early remobilised Holocene sediment from coastal barriers reworked as the shelf underwent erosional shoreface retreat (Figure 7-3).

7.3.3 Holocene Evolution Stage 3: highstand deposits

At approximately 5300 years BP a highstand of 2-3 m occurred. The highstand was for a duration of 500 to 1000 years and was followed by a slow regression to present sea-level. During this period parabolic dune development continued, and the raised sea-level enabled progradation over earlier sea cliffs. The majority of the marine embayment fill would have occurred during this period. The parabolic dune fields between Red Bluff and Three Mile Camp in southern Area Y suggest deposition occurred during a highstand, as they have prograded over a 3 to 5 m high sea cliff. During this highstand the marine embayments present in this area were populated by mangroves (Kendrick, 1990). The large saline flat in Area X displays clear evidence of mangrove development, primarily in the form of locally abundant gastropods, such as *Terebralia sulcata* (Born), a mangrove dwelling species. Local accumulations from this region are thought to be from aboriginal middens. The subsequent decline in the mangrove populations has been attributed to the barring of the embayments by coastal progradation, reinforced by Late Holocene regression, stranding the mangrove community (Kendrick, 1990).

7.3.4 Holocene Evolution Stage 4: regressive deposits

Sea-level has been declining since the end of the Late Holocene highstand to present. Beach ridge plains are the major depositional style of this 5300 year period. As shown in Figure 7-3, the regressive phase of coastal development is a prograding sequence from a relic-shoreline (often low cliffs) or from the seaward edge of a parabolic dune field. The width of the regressive phase of coastal development varies considerably along the coast. At some localities development is absent (where high Trealla Limestone cliffs abut the waters edge), whilst at others it is the only Holocene phase present (where shore-parallel beach ridges are banked up against a high Trealla Limestone cliff). Overall, regression dune plains usually vary between 20 to 500 m in width.

Modern parabolic dunes were also generated during this stage. These are younger than the bulk of the parabolic dunes along the coast, this is known due to stratigraphic relationships, geomorphology, colouration and vegetation cover. This final stage of dune development occurred when sea-level had fallen to current levels. Such dunes form when vegetation is sparse and strong oblique onshore winds mobilise older parabolic dunes and Holocene coastal sediments. These dunes are a clean white colour, in contrast to the older Holocene dunes that have been stained red from iron oxide-rich dust derived from the red longitudinal sand dunes to the east.

7.3.5 Holocene Evolution Stage 5: modern beach and foredune development

Active sandy beaches and modern foredunes are a result of the current active sedimentary system operating along the Ningaloo coast. Various beach and foredune morphologies exist (Table 6-1) and these are modified by seasonal changes, such as cyclonic events. Offshore processes control sediment supply to the coast, and vary depending on the offshore reef morphology.

7.4 Coastal Morphological Types

The coast adjacent to Ningaloo Reef (including Area X and Y) is composed of combinations of 7 end-member coastal morphologies (Figures 7-5 to 7-7). Whilst these seven types represent the main coastal morphologies, there are also occasional mixed examples.

7.4.1 Cliff Coast

The coast between Red Bluff to Three Mile Camp is predominantly cliff coast (Figure 7-5-A). Cliff coasts typically develop landward of reef passes, and tend to have a straight morphology due to a range of erosional processes. Wave action is significant in shaping cliffs; it consists of hydraulic forces (associated with water movement) and mechanical forces (particularly associated with sediment that is carried by waves) that dissipate at the coast instead of on the reef, thus transporting sediment alongshore. Physiochemical action (involving physical and chemical weathering by corrosive seawater), biological action and subaerial processes have also influenced the morphology of the cliff coasts in the Ningaloo Region. The reef to the south of the existing marine park (Red Bluff to Amherst Point) is less continuous and much narrower than further north, attesting to cliffs being developed in the absence of substantial reef. No major Holocene deposition takes place on cliff coasts due to the erosive nature of the system.

7.4.2 Parabolic dune coast

Many of the beaches adjacent to Ningaloo Reef experience high onshore wind energy, and a positive sediment budget, and hence can supply sediment to form parabolic dunes. Parabolic dune coast is present at numerous localities along the Ningaloo Coast, beginning at Amherst Point. They develop where the pre-existing topography is low enough in elevation to allow sand dunes, driven landward in front of an advancing transgression, to bury the initial topography, resulting in landward progradation of parabolic dunes (7-5-B). The prevailing wind in the Ningaloo region is a persistent southerly wind and this is evident along the coast as the parabolic dune deposits being located on the southerly side of headlands, hence, the prevailing wind direction has remained relatively constant during the last 10,000 years. The older, further inland parabolic dunes have been rubified due to impregnating sediment with iron oxides, abundant in inland dunes.

7.4.3 Cuspate Foreland

A series of cuspate forelands have developed in the lee of the Ningaloo Reef due to the effects of wave sheltering and circulation patterns within the lagoon (Sanderson, 1997) see Figure 7-5-C. A number of the cuspate forelands have two lobes of development, including Cape Farquar and Alison Point (7-6-A). The pre-existing topography that cuspate forelands develop upon is variable, and therefore probably not a major controlling factor in their distribution. They do however appear to be correlated with reef passes, which are sediment conduits.

7.4.4 Barred River Coast

Barred River Coasts are present at numerous localities in the north of Area Y where drainage is present (Figure 7-6-B). This area represents the only surface drainage of incised creeks within the study areas. A sand bar has accumulated between the creeks and the ocean at all such localities, however the presence of salt water fish in the creeks and small estuaries suggests occasional ocean inundation. Rock bars are often located adjacent to the sand bars on the landward side, indicating earlier coastal evolution. The westward flowing creeks drain to the ocean from the Giralia Range in the east, however the region's usually low rainfall results in limited drainage.

7.4.5 Cliff Coast With Pleistocene Reef Filled Embayments

A number of small embayments in cliff coast have been filled with the Last Interglacial Reefal deposits of the Tantabiddi Member (7-6-C). These embayment-fill reef deposits occur at numerous localities in Area Y, in both Trealla and Bundera pre-existing coastal terrains. The fabric of these raised reefs is well preserved but access is difficult.

7.4.6 Beach ridge coast

When sand supply to the beach is abundant but winds are insufficient for dune building, a beach ridge plain develops. Many of the beach ridge plains adjacent along the coast of Ningaloo Reef developed as prograding coasts during Late Holocene sea-level regression (7-7-A). Beach ridges include all relict sand plain ridges. They develop as semi-parallel features and may be wave and/or wind built landforms.

7.4.7 Pocket beach coast

Pocket beaches occur along the Ningaloo coast where narrow cliff embayments are located, and a minor indentation in a straight cliff line gives rise to sediment accumulation in the coastal hollow (7-7-B).

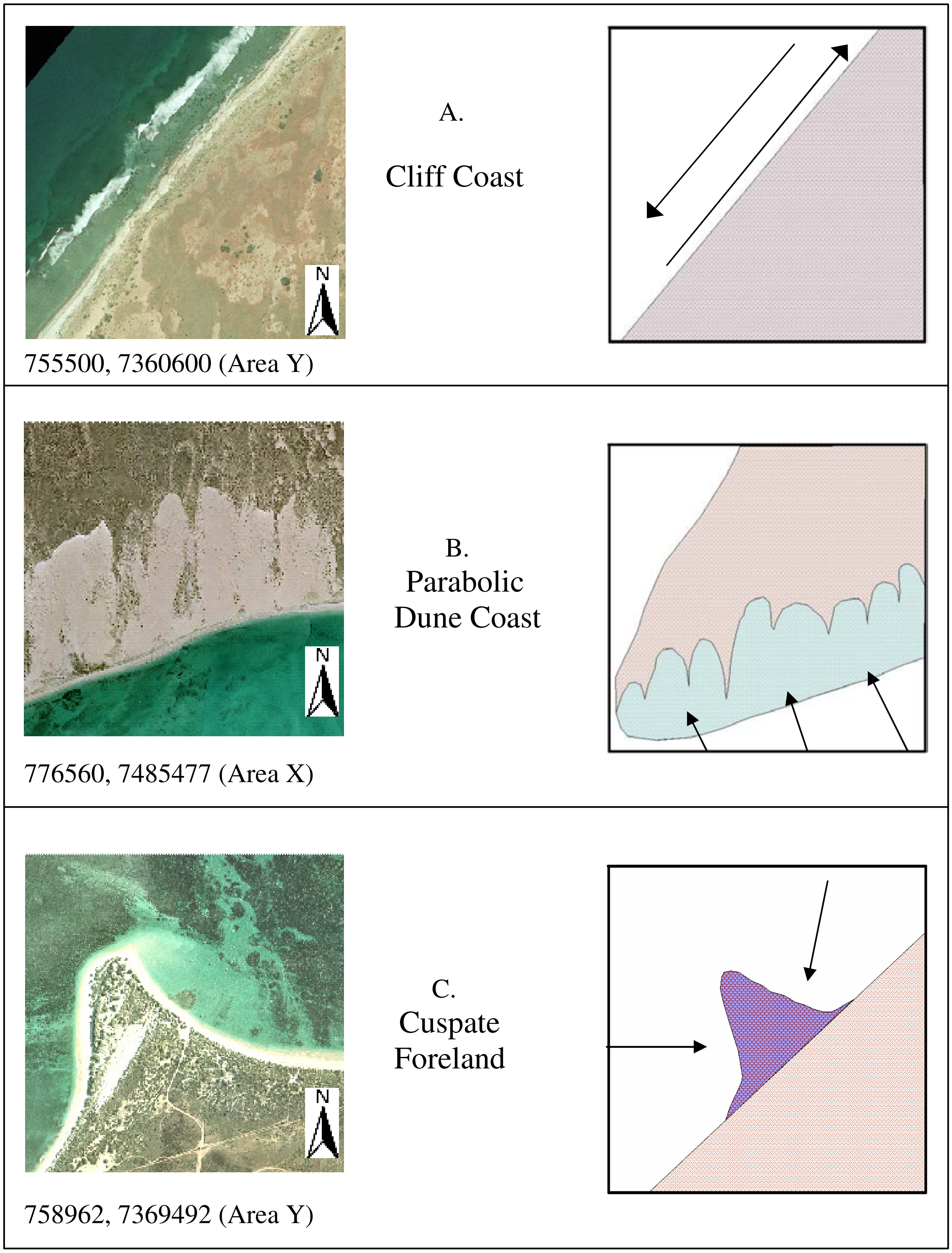


Figure 7-5. Coastal morphology types adjacent to Ningaloo Reef. Arrows in the diagrammatic sketch depict the Holocene sediment supply direction. The pink/purple represents the pre-existing topography.

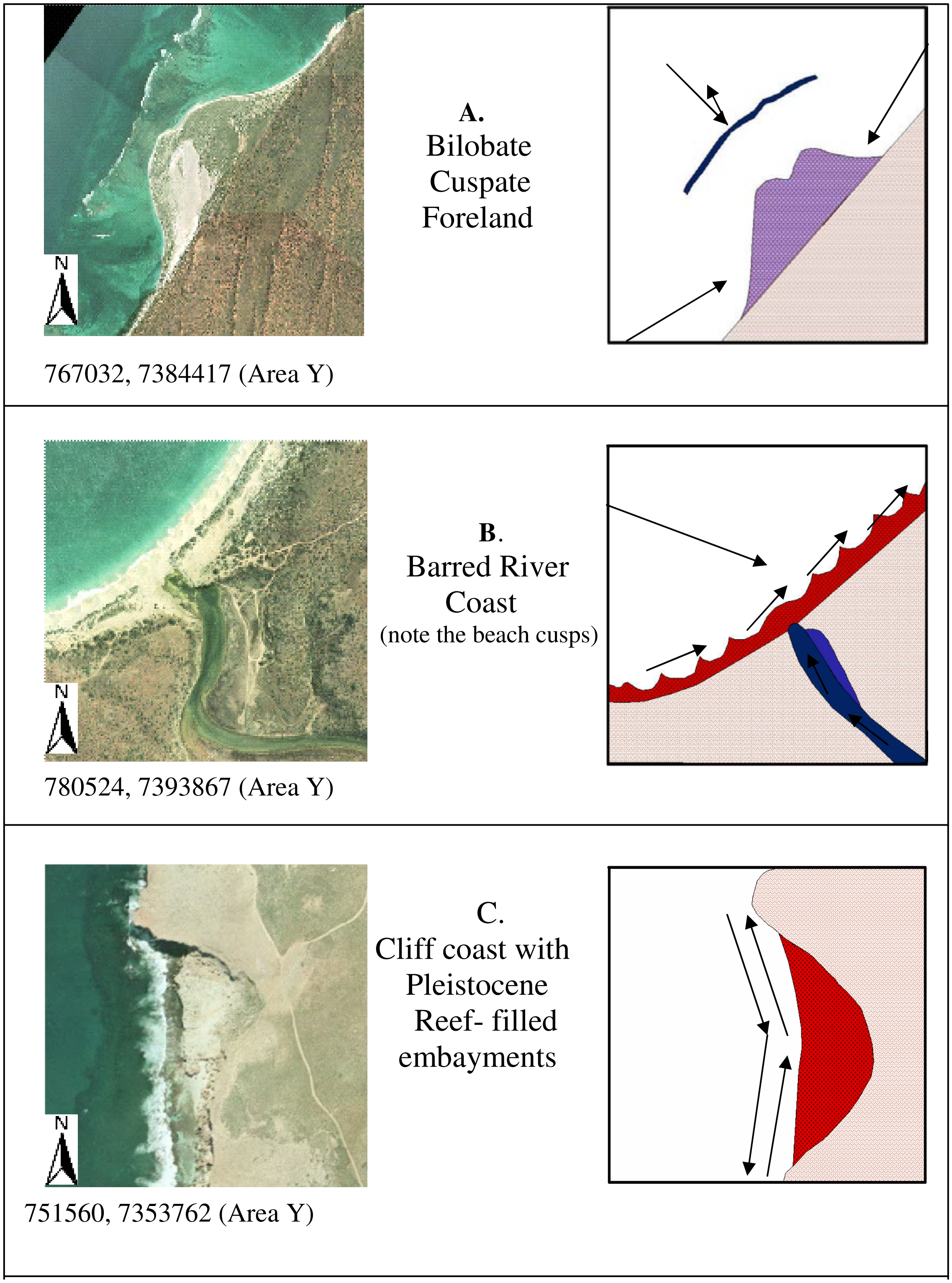


Figure 7-6. Coastal morphology types adjacent to Ningaloo Reef. Arrows in the diagrammatic sketch depict the Holocene sediment supply direction. The pink/purple represents the pre-existing topography.

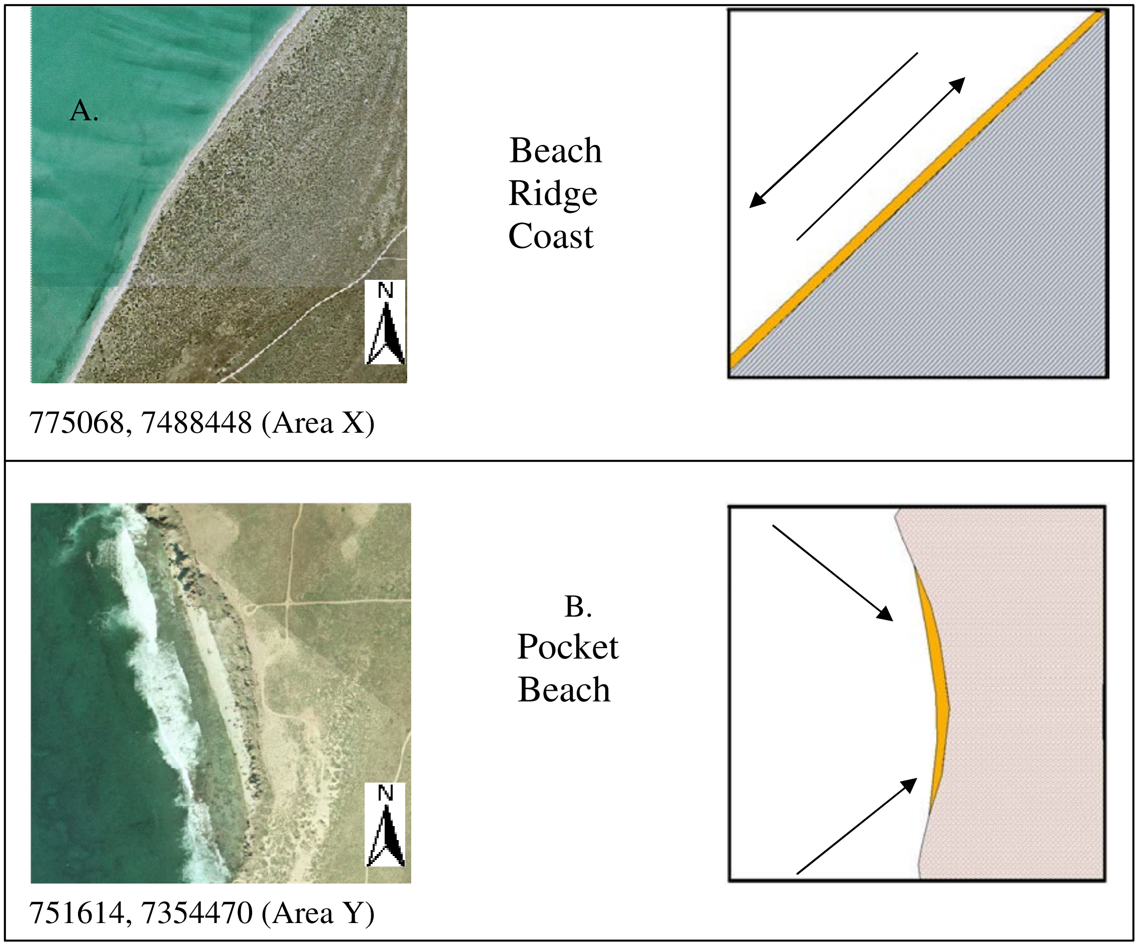


Figure 7-7. Coastal morphology types adjacent to Ningaloo Reef. Arrows in the diagrammatic sketch depict the Holocene sediment supply direction. The pink/purple represents the pre-existing topography.

8 SUBSTRATE CAPACITY AND ITS SPATIAL EXPRESSION

This chapter is designed to be read in conjunction with the supplied GIS data and/or the hard copy maps, specifically the land management maps that delineate the substrate capacity index and risk zones (Table 8-1). The risk zones are more visible utilizing the digital data.

The substrate capacity of a land unit categorises the levels of use and development that can occur without causing environmental damage or degradation. The term substrate capacity and the substrate capacity index (SCI) were developed to add value to the land system unit descriptions, making them more useful for land management purposes.

Substrate capacity 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 capacity include: unit thickness, stratigraphy, slope stability and angle, constituents and consolidation, topography and vegetation cover, (see 1.2.4 for a detailed description). Table 8-1 outlines the 23 land system units and their corresponding substrate capacity index.

<u>Very High Substrate Capacity (SCI= 5)</u>

The units classed as having a very high substrate capacity are all Pleistocene limestones, with the exception of the Trealla Limestone which is Tertiary in age. They

Table 8-1. Land system units and their corresponding substrate capacity index (SCI).

SCI	Land System Units
1 Very Low	Active beach, Modern foredune, Beach ridge plain (un-vegetated), Parabolic dune (active), Un-vegetated red sediment (blowout).
2 Low	Beach (rocky), Saline flat, Beach ridge plain, Cuspate foreland, Parabolic dunes, Linear relict foredunes, Tantabiddi reef member, Deflation basin.
3 Medium	Longitudinal dunes and sand plain, Red sediment sheet, Tantabiddi Terrace, Colluvial Plain.
4 High	Bundera Calcarenite outcrop, Calcrete.
5 Very High	Jurabi Member, Milyering Member, Muiron Member, Trealla Limestone.

have a non-existent to very thin cover of colluvial material. The Trealla Limestone crops out as a coastal scarp (in Area Y) which varies in distance from the coast, from an immediate coastal cliff to an inland escarpment that extends east beyond the study area.

The Pleistocene units express themselves as the foothills of the Cape Range (Area X, grid reference 777500, 7495000). The level of degradation possible on these units is negligible due to their consolidated state; therefore they are useful due to their impact resilience, in terms of future development along the otherwise predominantly fragile coast. There are a few locations along the coast of Area Y where there is a potential for rock falls or landslides from overhanging Trealla Limestone cliffs due to weaknesses along occasional joint planes in the unit. Of these localities, only one is frequented by people – Red Bluff camp site. At Red Bluff overhanging cliffs exhibit collapses along joint planes above a path that receives daily human traffic (Figure 8-1). The locality displays clear evidence of former boulder falls and should be recognised as a potential hazard to humans. A potential landslide would most likely take place after a heavy rain, as water saturation will significantly increase the unit's weight and lubricate fractures.

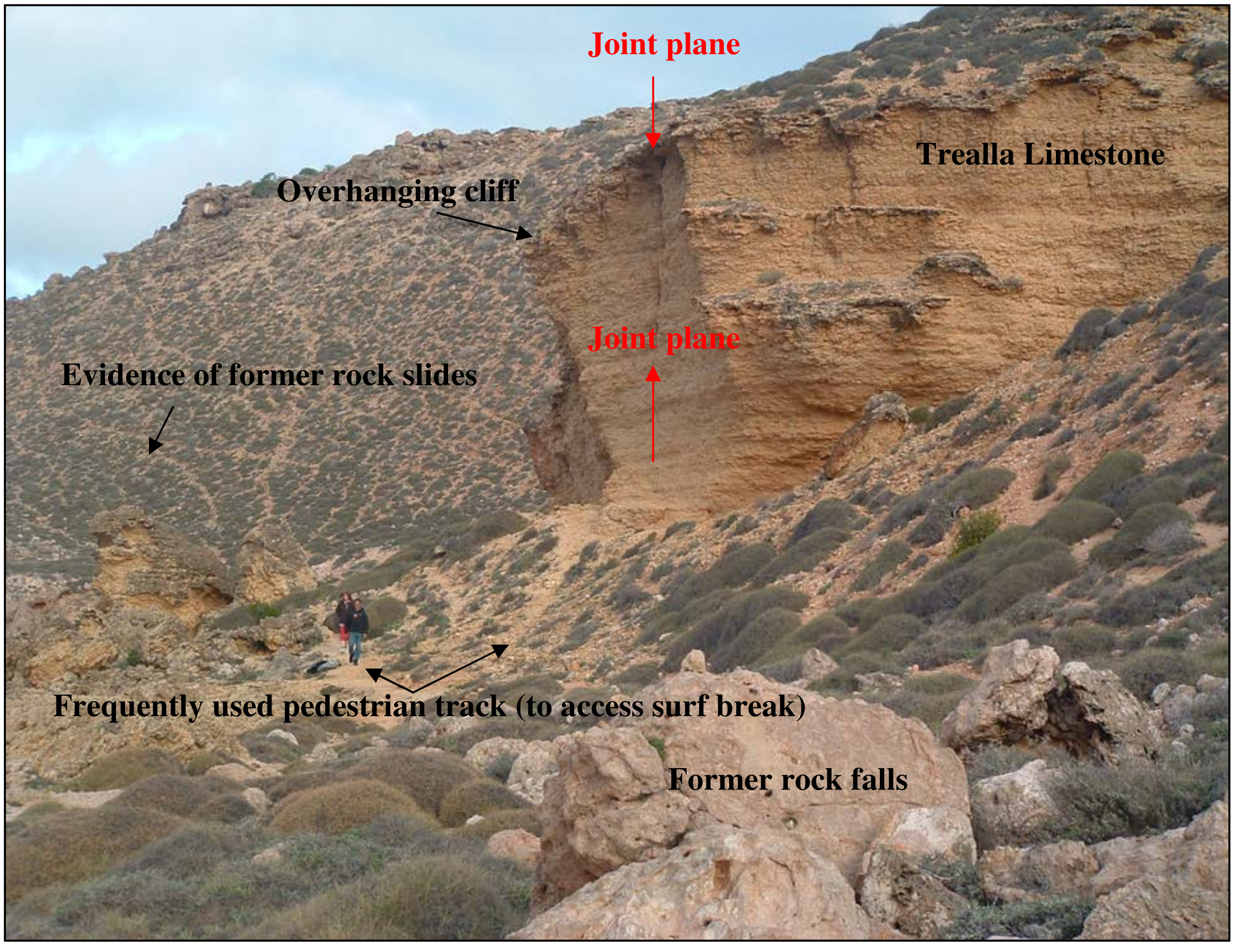


Figure 8-1. Natural, potentially hazardous cliff face at Red Bluff. There are numerous other faces similar to this in the Red Bluff precinct. Note the two people for scale.

High Substrate Capacity (SCI= 4)

Land units with a high substrate capacity are typically small isolated outcrops occurring as domes, or topographic highs (Table 8-1). They are composed of various units of calcarenite (Table 6-1) or calcrete, and typically have a very thin cover of colluvial material. However the isolated nature of these units makes them relatively insignificant in terms of land management.

Medium Substrate Capacity (SCI= 3)

Units of medium substrate capacity constitute the majority of the mapped areas in the form of the longitudinal dunes and sand plain, red sediment sheet, Tantabiddi Terrace and colluvial plain. These units exhibit medium to dense vegetation cover on top of unconsolidated compacted sand which overlies a limestone basal unit (Table 6-1). The only significant degradation in these units are small 'blowouts' of red colluvial sands in the longitudinal dunes and sand plain, mapped as a separate unit due to its different substrate capacity. These 'blowouts' are associated with areas of stock/fire damage and access track intersections. The Tantabiddi Terrace (Area X) is a predominantly flat limestone plain with a cover of 0.5 to 5 m of red unconsolidated soils and calcareous sands. The moderate vegetation and flat topography make this unit relatively resistant to 'blowouts'. Minimal degradation was observed on this unit during field work, the little degradation that is present is due to access track proliferation over locally mobile 'boggy' sections.

Low Substrate Capacity (SCI= 2)

Land units with a low substrate capacity are unconsolidated, low undulating plains to medium sloped dunes with minimal vegetation cover (Table 6-1 and Table 8-1). The sparse vegetation, unconsolidated nature of the constituents and the low to moderate dune slopes make these units susceptible to natural and anthropogenic impacts. These units are commonly the location of nodes of activity such as access points and camping sites due to their close proximity to the coast. High land use (via land access track or camping sites) commonly results in substantial areas of degraded dunes. Examples include Jane Bay Camp site (Figure 8-5) and Three Mile Camping ground (Figure 8-6).

Very Low Substrate Capacity (SCI= 1)

Land system units with a very low substrate capacity are unconsolidated, have very sparse to no vegetation, are commonly active, and display steep slopes to undulating topography (see Tables 8-1 and 6-1). Such characteristics make these units highly prone to erosion and remobilisation of sediment, which leads to the development of large denuded areas and ‘blowouts’. Typically, land units of a very low substrate capacity are situated immediately adjacent to the coast. The active sandy beach is commonly utilised by tourists, increasing the risk of degradation. Sand boarding was witnessed on large active parabolic dunes in Area X, a recreational activity which removes stabilising vegetation and leads to the gradual change in topography, resulting in sand mobilisation and ‘blowouts’. It is necessary to avoid access track development on land system units with a very low substrate capacity as it is inevitable that such interactions will lead to degradation.

8.1 Risk Zones

In order to highlight problem zones in Area X and Area Y, a systematic method of delineating risk zones was developed. Risk zones are areas of low substrate capacity that are highly utilized for track access and therefore are at substantial risk of degradation. Risk zones were identified as areas of land with a low or very low substrate capacity (SCI = 1 or 2) and high land use (greater than 7000 m^2 of buffered track area within four hectares). Appendix 1 contains the full description of the method used to delineate these zones. Hardcopy land management maps X, Y-south and Y-north present all the high use zones, with an overlay of the colour coded risk factor. These can be viewed at a much larger scale when viewing the GIS data in a digital format. A quantative assessment of the area of each land system unit affected by risk zones was completed (Figures 8-2 and 8-3), allowing for an assessment of the fragile land system units under the most pressure from human impacts in the two areas.

The majority of the risk zones were located at tourist nodes such as camping sites or regularly used track intersections. On the whole, Area X contained a higher percentage of risk zones compared to Area Y. The majority of Areas Y is cliff coast, and therefore not of low substrate capacity.

Area X receives a significantly higher number of vehicles than Area Y. This can be largely attributed to the presence of the Coral Bay to Yardie Creek road that runs through the area parallel to the coast. The track itself is mostly accessible by 2WD with the exception of a few sandy blowouts and the Yardie Creek crossing. There are a number of indiscriminate tracks and minor detours which have been created near the main track due to sandy, 'boggy' or inundated sections. Figure 8-4 depicts the Ningaloo Road connecting to the Coral Bay-Yardie Creek Road on a sand-inundated saline flat. A number of risk zones have emerged due to the erratic nature of the tracks. The substrate is 'boggy' and slippery even after a relatively low rainfall event which leads to the proliferation of tracks. The tracks have caused the loss of salt tolerant vegetation, and erosion via red sediment blowouts of the otherwise stable sand sheet

(Figure 8-2). The aerial extent (in m^2 and %) of risk zones in the Ningaloo Region (Area X).

which overlies the Tantabiddi Terrace (in the north of Figure 8-4). This risk zone is responsible for the large high use component (Figure 8-2) associated with a saline flat in Area X.

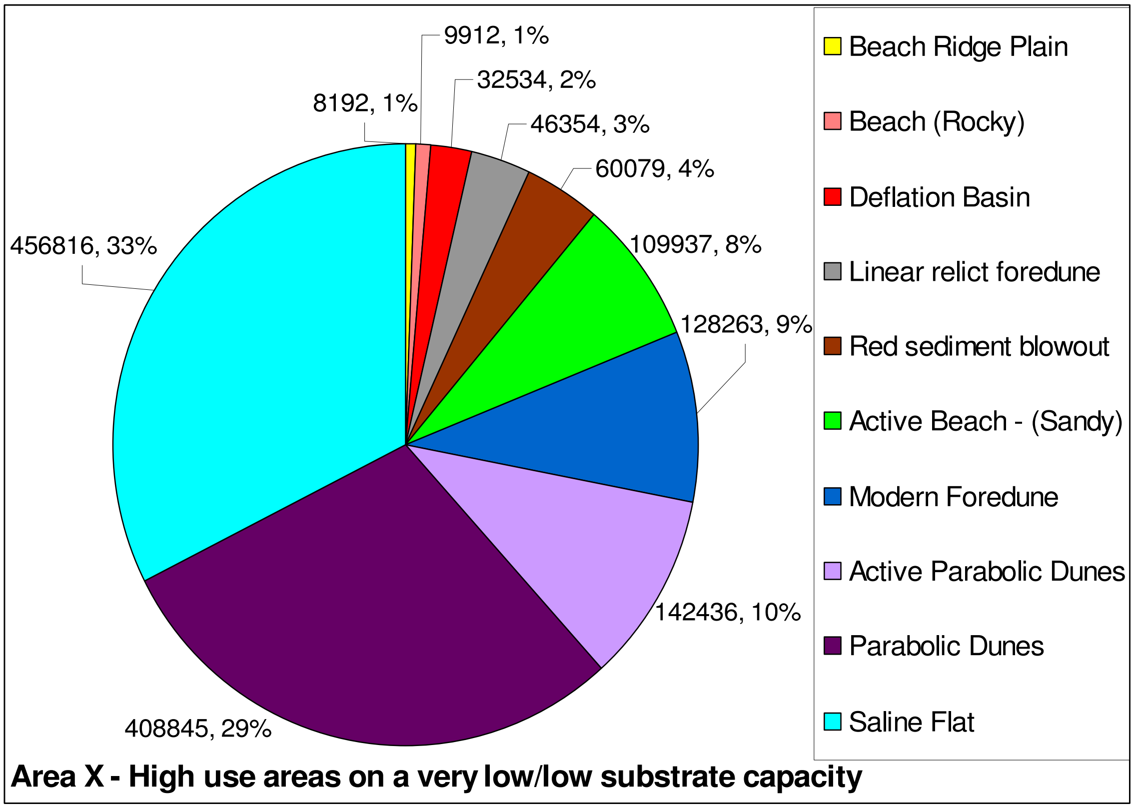


Figure 8-2. The aerial extent (in m^2 and %) of risk zones in the Ningaloo Area (Area X).

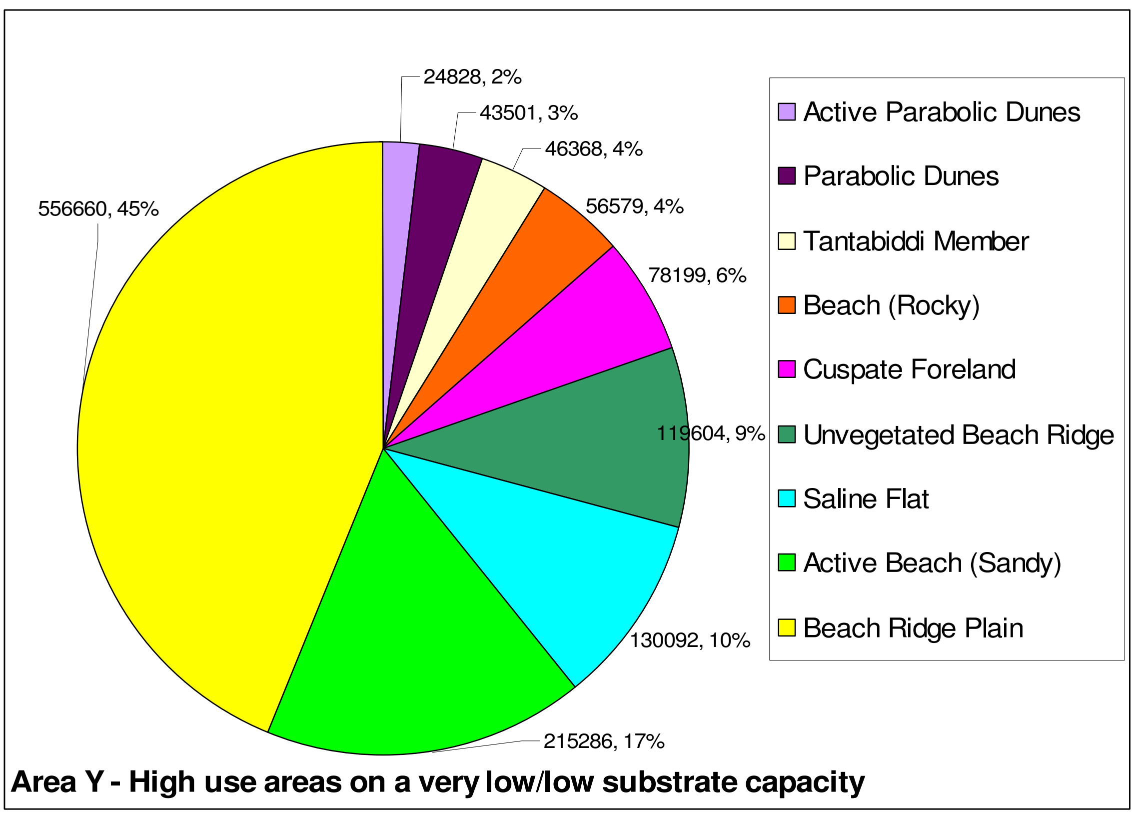


Figure 8-3. The aerial extent (in m^2 and %) of risk zones in the Gnaraloo Area (Area Y).

Figure 8-5 depicts the risk zones associated with a camp site near Jane Bay on Area X. The camp site itself contains degraded vegetation, and is located where the orange risk zones appear (along 778500). Of higher risk is the red coloured risk zone that runs adjacent to the coast which is a track highly utilised for recreational purposes (fishing, snorkelling and recreational four wheel driving along the beach).

Area Y has a relatively small area of risk zones in comparison to Area X. The majority of the risk zones are located on beach ridge plains (45%), followed by active sandy beaches (17%) as shown in Figure 8-2. The beach ridge plain risk zones are dispersed along the 70km coastal length of Area Y. The active sandy beach risk zones are predominantly located in the north of Area Y, where informal camping is occurring on Warroora Station. Three Mile Camp site contains some high risk zones that have the potential to increase in size (Figure 8-6) if not managed correctly. Figure 8-7 illustrates the lack of risk zones occurring on a low substrate capacity at Red Bluff Camp.

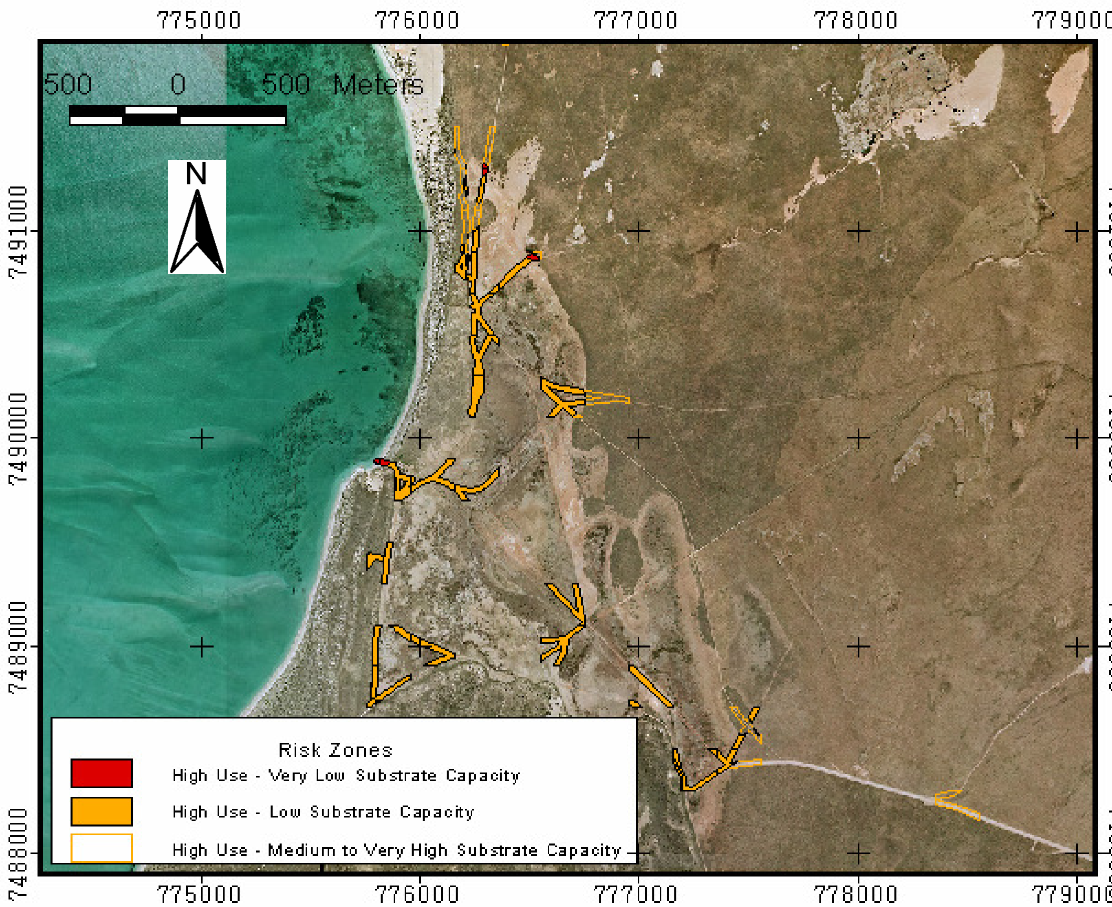


Figure 8-4. Risk zones associated with access tracks on Ningaloo Station (Area X).

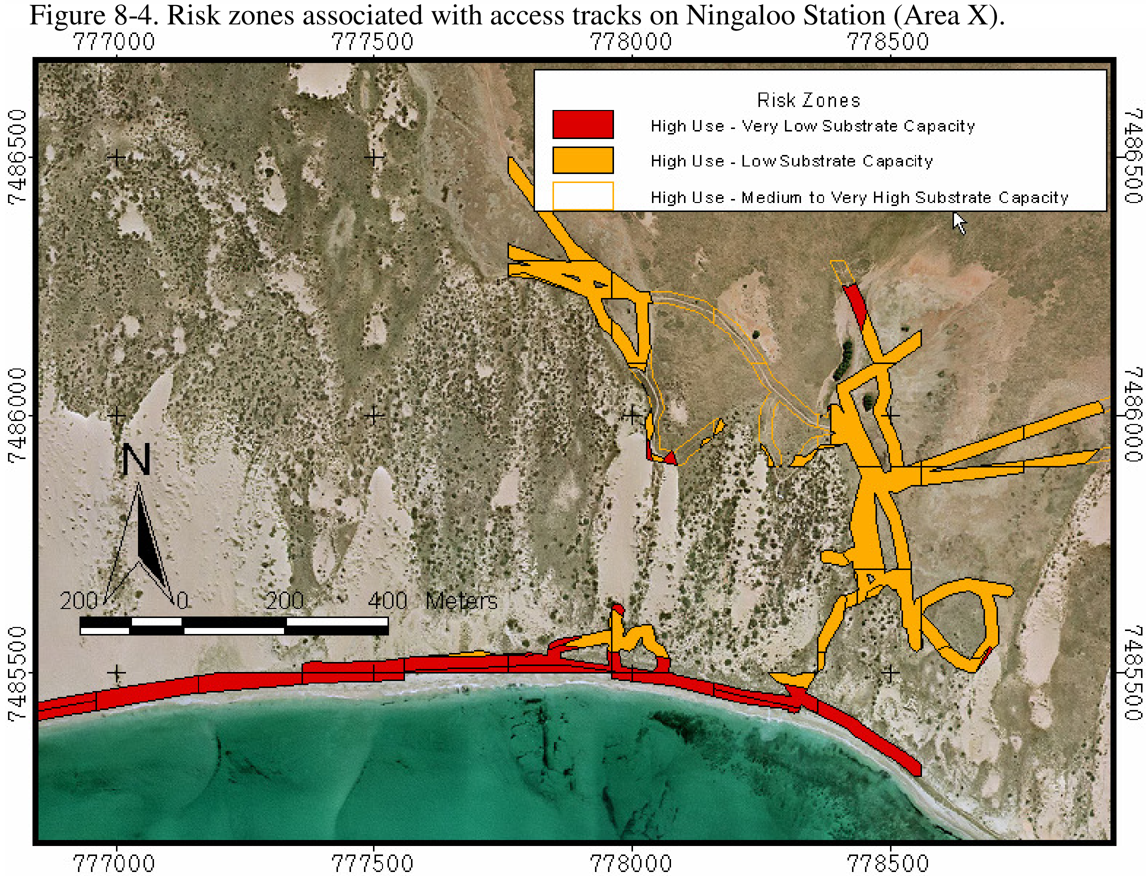


Figure 8-5. Risk zones associated with the Jane Bay camp site on Ningaloo Station (Area X).

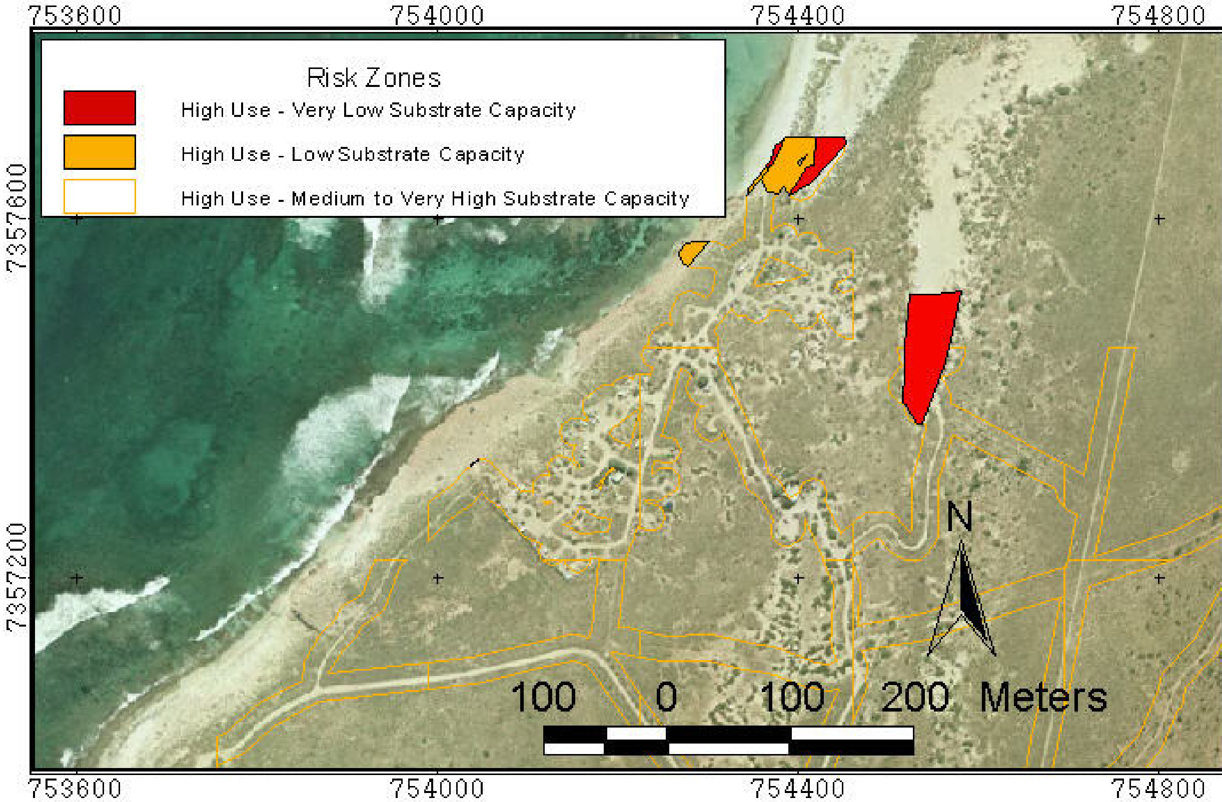


Figure 8-6. Risk zones at Three Mile Camp.

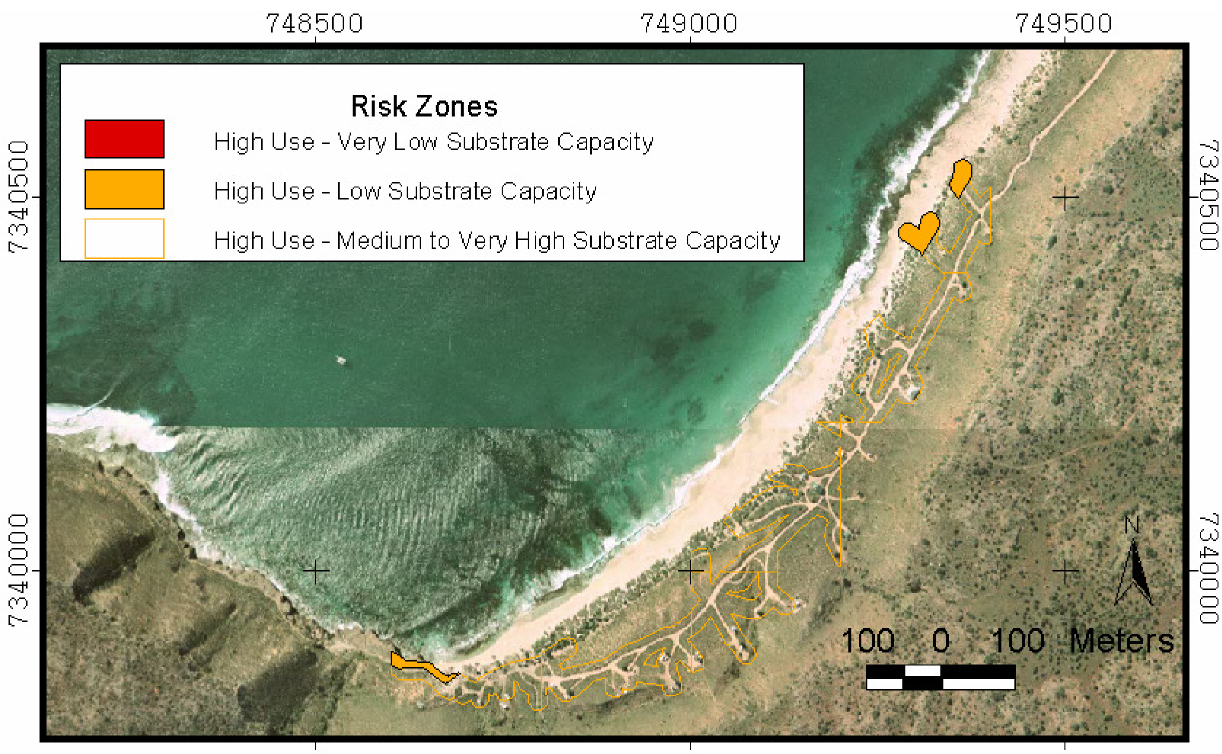


Figure 8-7. Risk zones at Red Bluff Camp.

9 CONCLUSIONS

Area X (Chabjuwardoo Bay to Norwegian Bay) was chosen as a study area due to the comparative lack of understanding of the geological and geomorphological processes at work in the area and its potential as a future node of development. Area Y (Red Bluff to Alison Point) was selected due to the lack of knowledge of the coastal geology and landforms adjacent to southern Ningaloo Reef, and due to its potential to be reclassified as Marine Park in the future.

Poor access track development and lack of environmental maintenance is the greatest anthropogenic impact on the coast adjacent to the Ningaloo Reef. This is followed by the environmental impacts associated with nodes of activity such as camping sites. Despite the various land and tourist management strategies put in place by the pastoral station managers, significant degradation of this fragile environment is occurring. This degradation predominantly occurs as erosion and remobilisation of sediment, triggered by the loss of vegetation. Such degradation is more pronounced in Area X than in Area Y. This is a result of Area X receiving significantly higher tourist and vehicle numbers due to its proximity to the Cape Range National Park, Coral Bay and Yardie Creek, and its highly sought after swimming and snorkelling beaches. Another contributing factor to Area Y being less degraded is the lack of Late Holocene deposition, which includes substrates that are the youngest, least stable and most fragile system.

The coast adjacent to Ningaloo Reef is highly variable, as the geology and geomorphology of Area X and Area Y illustrates (rugged cliff coastal geomorphology in the south opposed to sandy beaches in the north). Area Y is composed of a Tertiary limestone escarpment that runs parallel to the coast, and is overlain by Pleistocene desert dunes. To the west of the scarp lie variable amounts of Holocene and Pleistocene depositions, with occasional sections where neither are present. The coastal zone adjacent to Area X is composed of a Pleistocene limestone hinterland and a Holocene sandy fringe. Oceanography, climatic variations (past and present) and sea-level variations are the dominant physical processes responsible for evolving and modifying this coast adjacent to Ningaloo Reef.

The pre-existing Tertiary topography in Area Y of Trealla Limestone has strongly dictated the available space for Holocene deposition. In contrast, in Area X the initial Pleistocene topography of Bundera Limestone provided the pre-Holocene depositional surface and created nodes of sedimentation associated with limestone headlands. Ningaloo Reef has dictated local current flow and, in turn, sedimentary processes. The reef has also acted as a barrier by refracting wave energy, which has controlled sediment transport and coastal morphology.

Both areas studied show evidence of tectonic uplift, in the form of the Cape Range terraces in Area X, and raised Tertiary Trealla Limestone sections in Area Y, such as the Red Bluff headland. Of geological significance in Area X are the karst systems in which stygofauna and troglobites inhabit. Area Y contains pristine Last Interglacial Reef outcrops.

Land system units with a very low to low substrate capacity (SCI = 1 or 2) are sparsely vegetated, unconsolidated, commonly mobile, with steep slopes and undulating topography. These characteristics make such regions prone to the remobilization of sediment and erosion, and thus prone to degradation. These typically Holocene units are usually located within 1 km of the waters edge. Land system units with a medium to high substrate capacity (SCI = 3, 4 or 5) consist of consolidated limestone with a thin to non existent cover of colluvial material, and are well vegetated. The level of degradation possible here is reduced due to the increased erosion resistance afforded by the consolidated substrate and by the stabilising vegetation cover.

IMPLICATIONS FOR LAND MANAGEMENT

The delineation of risk zones by GIS analysis of track density and substrate capacity identified areas of land particularly at risk of degradation due to a combination of substrate characteristics and type and intensity of land use. The information produced in this study will be of direct benefit to land managers as it quantifies impacts on the coastal zone and promotes the development of more effective management strategies to reduce the current risk zones. A major review of land management practices in the region is currently being undertaken by government agencies, and the data presented in this dissertation, in particularly the land management data, will aid in future planning proposals along the Ningaloo coastal zone.

10 RECOMMENDATIONS

- Continued detailed coastal mapping of the coast adjacent to the Northern sector of Ningaloo Reef should be undertaken as part of the continued effort to develop the spatial database currently being expanded by CALM and to delineate risk zones.
- The major risk zones should be addressed by an appropriate environmental body to prevent further degradation of these fragile areas in close proximity to the Ningaloo Reef.
- The risk zones associated with formal camping sites should be addressed by the current pastoralist care taker system in place at the various stations.
- Hazard signs should be erected at the base of the Red Bluff cliff face warning pedestrians of potential rock falls/landslides.
- Additional signs should be erected directing tourists to camp sites, with the aim of reducing access tracks caused by disorientated drivers.
- Delineation of approved access tracks.
- Blocking and stabilising of degraded access tracks.
- Land managers/pastoral station caretakers should avoid allowing camping sites on low substrate capacity units (SCI = 1 or 2) in an effort to reduce environmental degradation of the fragile coastal zone.
- The above recommendations should be tackled within the context of a Land Management Plan for the Ningaloo region.

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APPENDIX

1. **Reasoning for the high use area of 7000 m^2 and the 25 m 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 7000 m^2 of track in a 4-hectare square was used (see 3.2 GIS for the description of the process). The 7000 m^2 cut off was derived from both quantitative and qualitative methods and equates to a track length of 280 m [buffer width (25 m) x track length (280 m) = high use area (7000 m^2)].

Once an overlaying grid had been attributed with track density, in the form of area counts of the buffer per four hectare grid cell, a histogram was produced of the area per cells (see appendix charts 1 and 2). 7000 m^2 was deemed the best divide between average land use and high land use. Previous assessments of high land use (Blackwell, 2002) have derived similar results.

This initial judgment was then checked statistically (calculating the mean, standard deviation and variance) by comparing the two areas (Areas X and Y). These calculations provided similar results indicating that the cut off point of 7000 m^2 as a high risk zone could be used for the entire coast adjacent to Ningaloo Reef . The value of 7000 m^2 was also checked by visual assessment. This visual assessment led to rarely used track being omitted from the final calculations. After applying these methods, the cut off point of 7000 m^2 of track per four hectares was deemed appropriate as a consistent way of delineating high use zones.

A buffer of 25 meters was applied to the access tracks during the delineation of high land use zones (see 3.2 GIS for an explanation of method). The average track width is approximately 5 m wide. Based on field observations, an area of 10 m either side of a track has the potential to be affected by that track in the near future. Hence 25 m was derived (5 m average track width plus 10 m either side of the track).

The grid size of 200 m by 200 m (equivalent to four hectare cells) was deemed an appropriate cell size based on trial and error. A number of grid sizes were tested, and assesses visually and statistically. Grid spacing smaller than 200 m tended to utilise too much computer memory which led to frequent computer malfunctions due to the increased data generation. Four hectare cells were deemed an accurate grid measure; however as with all GIS do contain minor limitations (see 1-2-7). The 7000 m^2 high use buffered area only apples to four hectare grid cells.

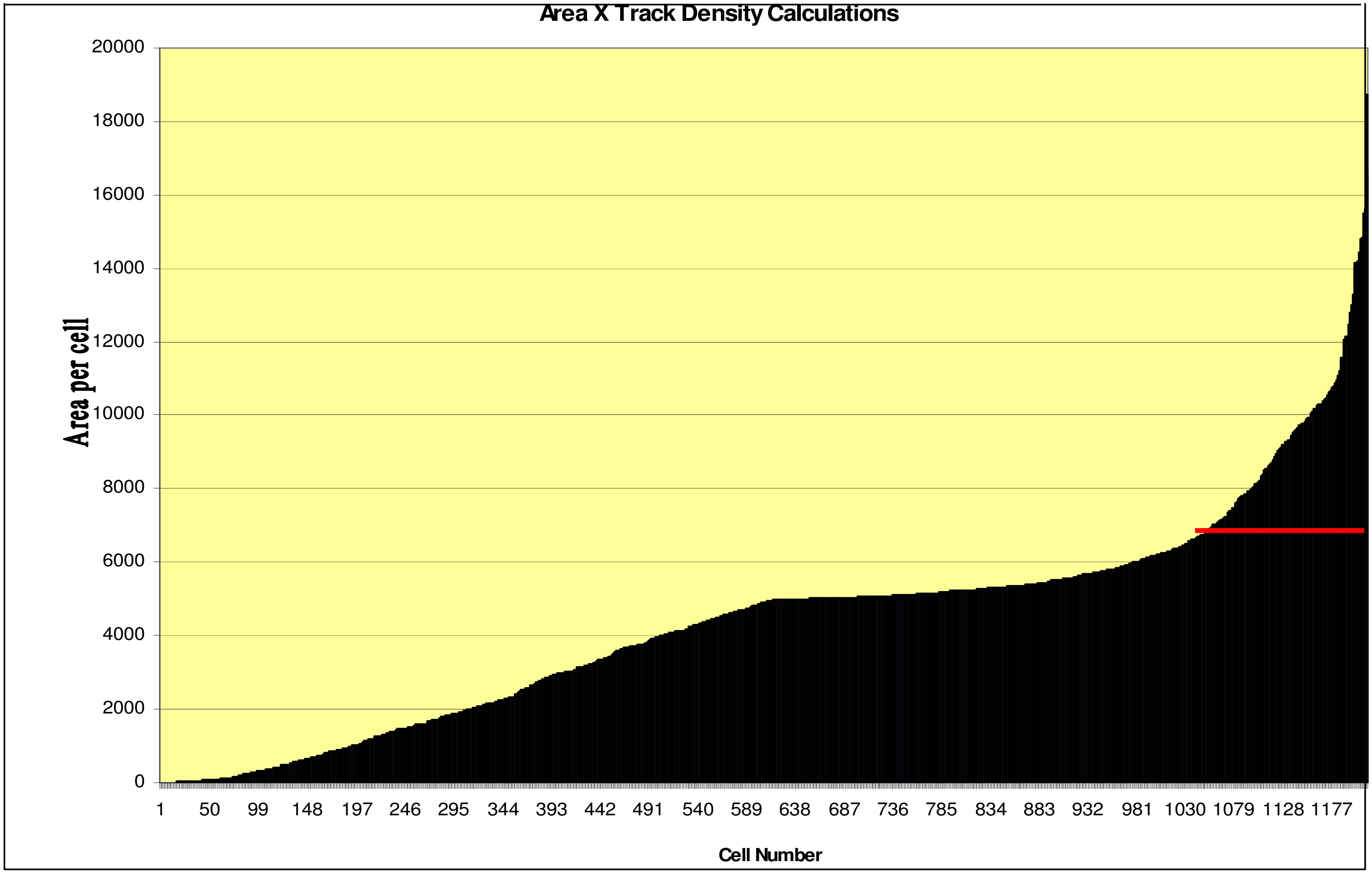


Chart 1: Histogram of buffered track area counts (m^2) in 4 hectare cells for Area X (Ningaloo Region). Above the red line are the high use zones.

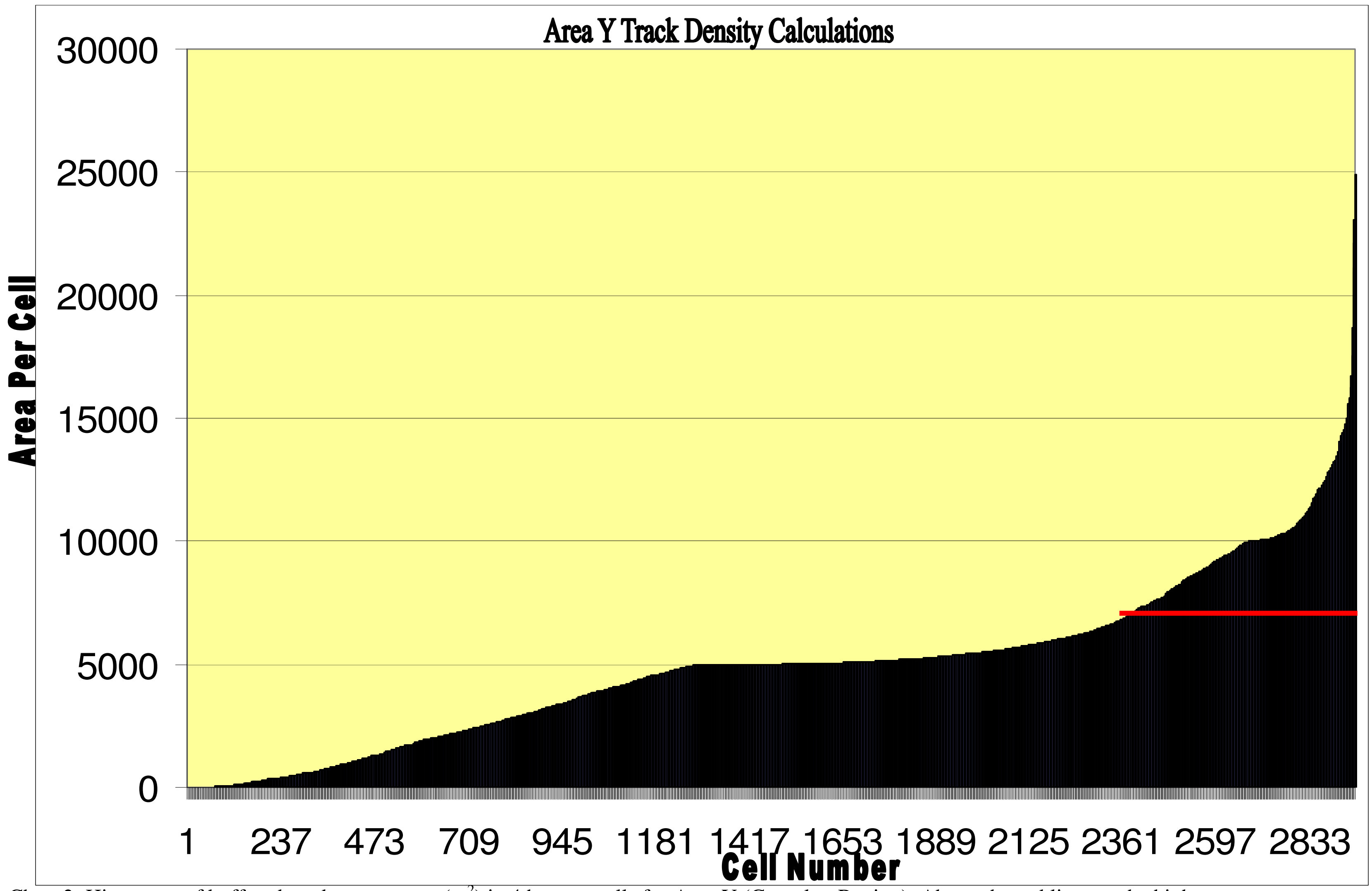


Chart 2: Histogram of buffered track area counts (m^2) in 4 hectare cells for Area Y (Gnaraloo Region). Above the red line are the high use zones.

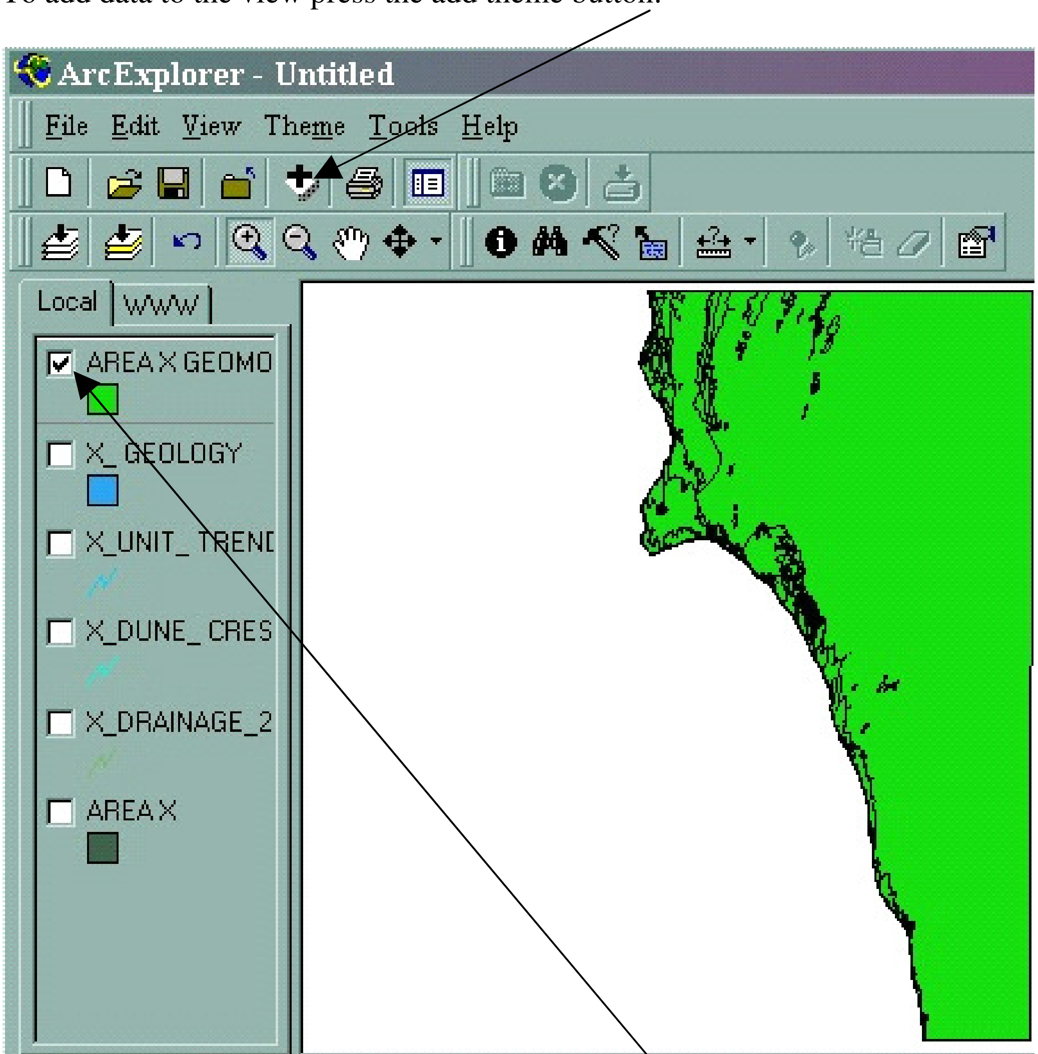
2. GIS viewing instructions

The accompanying compact disc is designed to allow interactive viewing of the GIS data created for the project. This data will be beneficial to land planners/managers and will prove a valuable tool in future developments along the coast.

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 button.



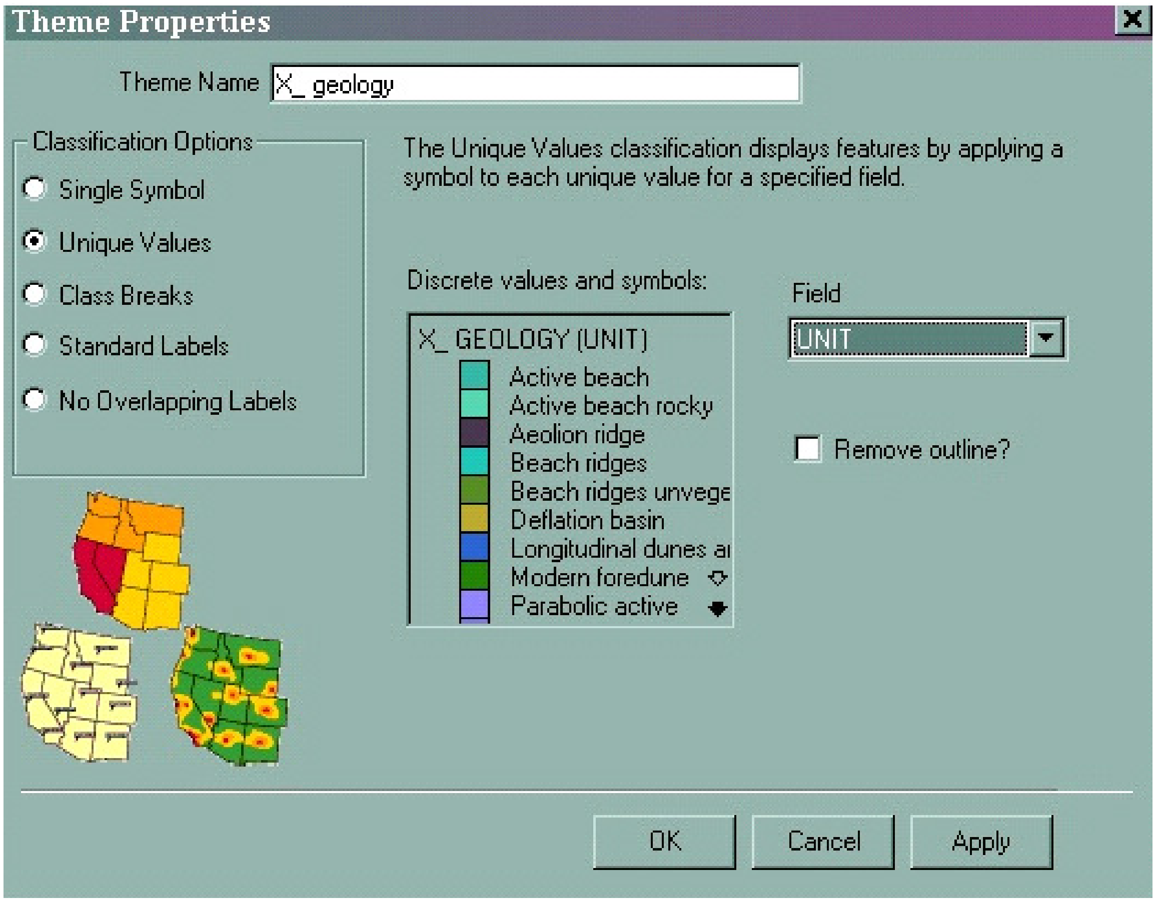
To make a theme active tick the box next to its title (see above).

Add all the data you require (geology, access tracks, risk zones….).

Note: the more images that are active, the slower it will run so only keep active the themes you need.

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

The following window will appear. For all themes use the “unique values” classification option and choose “unit” as the field for geology, “type” for access tracks and “capacity” for substrate capacity.



The program has a substantial help menu.

Digital versions of the map sheets and dissertation are also provided for reference purposes.

3. GOLDEN GHOST CRAB ABUNDANCE ON GNARALOO STATION

Date sighted: 21st June 2003 (all day)

Common name: Golden Ghost Crab

Predicted Species: *Ocypode convexa* (Family Ocypodidae)

Crab description: Bright yellow to golden coloured crab with black eyes on stalks. The average carapace was 45 mm wide.

Locality: On the coastal strip between Cape Farquhar and Amherst Point (between the locked gates)

Distance inland: From the shore line up to 4 km inland

Weather: 25ºC warm and sunny. However the night before they were sighted, approximately 3 cm of rain fell.

Above: Photograph of a golden ghost crab

Comment: There was a very high abundance of these crabs between Gnaraloo Station's locked gates. This could be due to the lack of human traffic, the crab's migration after the rain, or other reasons. In some places on the four wheel drive track there were more than ten crabs per square metre. Surprisingly there tended to be more crabs inland on the red linear desert dunes/sand plain than on the white sand nearer to the beach. During 2½ weeks mapping the coastal strip between Quobba Station and Ningaloo Station, it was only between the locked gates that such a large number of crabs were present. This species of crab has been identified as an indicator of human impact on beaches (Barros, 2000); this suggests their abundance is due to the lack of vehicles between the locked gates. It has been shown that track development near the beaches where crabs live, affects the exchange and supply of sand to the dune system and can interfere with the movement of many animals, such as ghost crabs (Barros, 2000).

4. Petrographic Descriptions

Specimen Number RB1

Location description..	Relict dune deposit on the north side of Red Bluff headland
Colour………………	Cream
Unit…………………	Bundera Aeolian Skeletal Grainstone
Structure…………….	Steeply dipping (35º) beds
Approximate age……	Pleistocene
Grain size…………...	Medium
Grain sorting………..	Well sorted
Grain roundness..…...	Rounded with moderate sphericity
Porosity…………......	High
Topography……..….	Rugged outcrop approximately 4 m high
Stratigraphy…...…….	Lying above of a 60 cm thick lagoonal/beach reworked fragmental sand sheet that lies directly on the Last Interglacial Reef.

Constituents	Comments	%Total
Calcareous/Coralline Algae		64
Molluscs		12
Forams		10
Quartz		8
Cement		5
Dolomite	Rhombic shaped zoned grains	1

Interpretation: The steep dipping angle of the beds and the grain morphology indicates aeolian origin.

Remarks: Very rarely do you see the aeolian phase sitting directly on the reef (this is the only such contact visible on the entire coast adjacent to Ningaloo Reef).

Specimen Number RB40CL

Location description..	Base of Red Bluff headland on southern side of headland
Colour………………	Cream
Unit…………………	Bundera Skeletal Grainstone
Structure…………….	Horizontal layers
Approximate age……	Pleistocene
Grain size…………...	Fine to medium
Grain sorting………..	Well sorted
Grain roundness...…..	Rounded, moderate sphericity
Porosity…………......	High
Topography……...….	Undulating topography
Stratigraphy…...…….	Overlying the Tantabiddi Last Interglacial Reef.

Constituents	Comments	%Total
Calcareous/Coralline Algae		60
Molluscs		10
Forams		10
Echinoid spines		8
Quartz		6
Cement	Whisker cements, aragonite	4
K-feldspar		2

Interpretation: A relict dune unit

Remarks: Plenty of open void space, clean grains (very little staining).

Specimen Number 49CL

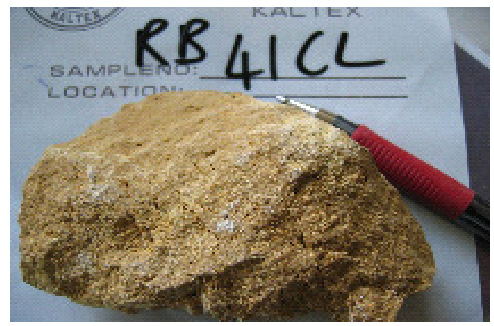
Location description..	Parabolic dunes adjacent to low Bundera limestone cliffs (South Ningaloo Station).
Colour………………	Cream to light brown
Unit…………………	Parabolic dunes.
Structure…………….	Unlithified
Approximate age ……	Early Holocene
Grain size…………...	Fine to medium
Grain sorting………..	Poor
Grain roundness...…..	Well rounded
Porosity………….…..	Unlithified
Topography……...….	Dunes
Stratigraphy…...…….	Overlies Bundera Limestone

Constituents	Comments	%Total
Calcareous/Coralline Algae		45
Forams	Reworked with micrite cements infilling the shells cavities/chambers	20
Lithoclasts		20
Coral	Difficult to detect the coral structure due to weathering (correlated with age)	5
Quartz		5
Molluscs		5

Remarks: Most grains contain an iron oxide orange coloured rim, which gives the unit a dirty brown colour. The source of these iron oxides is likely to be the red desert dunes. Hence the dirty coloured dunes are a result of impregnation of iron oxides derived from the Pleistocene red desert dunes located adjacent to white Holocene dunes.

Specimen Number RB41CL

Location description..	Wave base platform at Red Bluff
Colour………………	Light brown/orange
Unit…………………	Dolarstone
Structure…………….	Very dense
Approximate age……	Tertiary
Grain size…………...	Very fine
Grain sorting………..	Very well sorted
Grain roundness….....	Grains are rhombic
Porosity…………......	Very low
Topography……...….	Slightly dipping seaward platform
Stratigraphy…...…….	Overlain by the Last Interglacial Reef



Constituents	Comments	%Total
Dolomite	Rhombic shaped grains with very strong zonation	90
Glauconite	Blue in cross polarized light	3
Cement	Micritic rods	3
Porosity	Moldic pore space	3
Zircon or Monzonite		1

Interpretation: A tightly interlocked, almost complete replacement dolomite with considerable zonation. Extremely faint fabric visible in small pockets suggests recrystallised pelital limestone as the primary rock type which was then dolomatised. Dolomite most likely formed at the water interface at the time of deposition. Possible Trealla Limestone.

Remarks: Covered with modern day living aquatic organisms

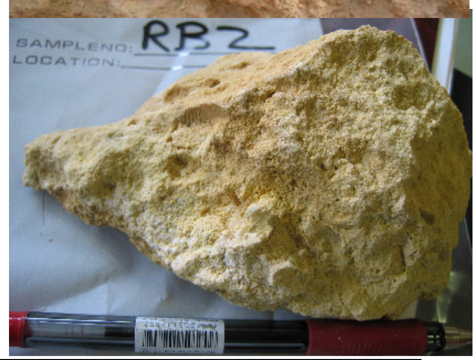
Specimen Number GN1CL

Location description..	Upper surface of active parabolic dune
Colour………………	White
Unit…………………	Active Parabolic dune
Structure…………….	Unlithified
Approximate age……	Holocene
Grain size…………...	Fine to medium
Grain sorting………..	Poor
Grain roundness...…..	Good
Porosity…………......	High ≈20%
Topography……...….	Barren/mobile 10m high parabolic dune
Stratigraphy…...…….	Overlies stationary Holocene parabolic dunes and Pleistocene sand plain.

Constituents	Comments	%Total
Calcareous/Coralline Algae		55
Molluscs		20
Quartz		8
Forams		6
Bryozoans		5
Lithoclasts	Contain trace amounts of micrite cement	4
Cement	Micrite	1
Echinoid spines		1

Remarks: A protective fence has been constructed alongside the fragile dunes in this area(southern Area Y), which has reduced vehicle access. Old vehicle tracks in this area have begun to naturally rehabilitate.

Specimen Number RB2



Location description..	Uplifted recrystallised headland at Red Bluff
Colour………………	Cream to pale yellow
Unit…………………	Trealla Limestone/Grainstone
Structure…………….	Predominantly calcretised
Approximate age……	Tertiary
Grain size…………...	Medium to Coarse
Grain sorting………..	Poor
Grain roundness...…..	Moderate
Porosity…………......	Low
Topography……...….	Visible as cliffs along the coast, sink holes/karst systems within the unit.
Stratigraphy…...…….	Defines the modern coast. Red Pleistocene desert dunes and sand plain overlie most of the Trealla.

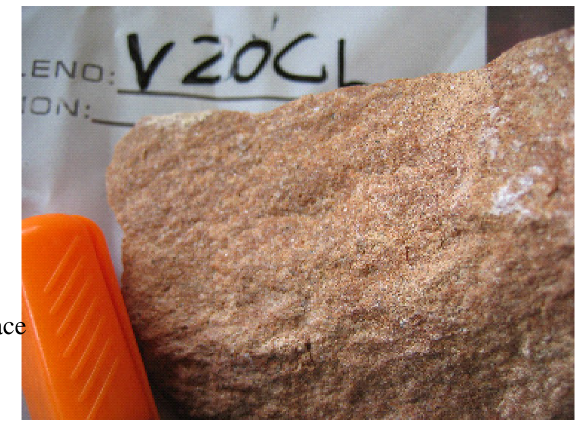
Constituents	Comments	%Total
Bryozoans		20
Forams	Species include: Numulita, Lepidocyclona	20
Echinoid spines/plates/discs		20
Calcareous/Coralline Algae		10
Molluscs		10
Pelecepod	Sand dollas = discoid cyclona=flat echinoid=substrate dweller	10
Coral		5
Lithoclasts		3
Quartz		2

Interpretation: Trealla Limestone is typically indicative of deposition in shallow, agitated waters, part of it was probably deposited in a lagoonal environment, with intermittent emergence (Denman and Van de Graaff, 1978).

Remarks: Red Bluff has the best Trealla Limestone outcrop along the coast as it is the only site that has not been predominantly calcretised. A variety of insitu shells are visible on a large weathered surface (pictured above). The foraminiferal faunas within the Trealla Limestone indicate a latest Early Miocene to Middle Miocene age (Denman and Van de Graaff, 1978).

There are numerous fractures in the Trealla which give rise to near vertical break aways and extensive scree slopes.

Specimen Number: V20CL



Location description..	Raised terrace on Ningaloo Station
Colour………………	Pale orange to pink
Unit…………………	Muiron Terrace (Grainstone)
Structure…………….	Predominantly calcretised and recrystallised
Approximate age……	Pleistocene
Grain size…………...	Fine
Grain sorting………..	Well sorted
Grain roundness...…..	Well rounded
Porosity…………..….	Low
Topography……..….	Raised Terrace
Stratigraphy…...…….	Overlying Milyering Terrace

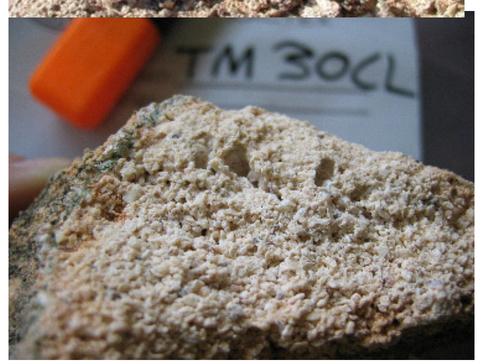
Constituents	Comments	%Total
Quartz		70
Cement	Predominantly micrite cement with pockets of blocky cement	25
Forams		5

Interpretation: Upon geomorphological inspection this unit appeared to be the Vlaming Sandstone, however the presence of forams suggests it is a component of the Muiron Member.

Remarks: Based on the above findings it is probable that the calcretised ridge to the East of the Muiron Terrace is calcretised Vlaming Sandstone (see map Area X).

Specimen Number: TM30CL

Location description..	Cliff coast south of Three Mile Camp
Colour………………	Cream
Unit…………………	Bundera Limestone (Grainstone)
Structure…………….	30 cm near horizontal blocky beds
Approximate age……	Pleistocene
Grain size…………...	Coarse
Grain sorting………..	Well sorted
Grain roundness...…..	Subangular to subrounded
Porosity………….…..	High
Topography……..….	Beach cliff approximately 8 m high (of which the upper 3 m is TM30CL)
Stratigraphy…...…….	Overlies the last interglacial reef (thickness of 5 m).



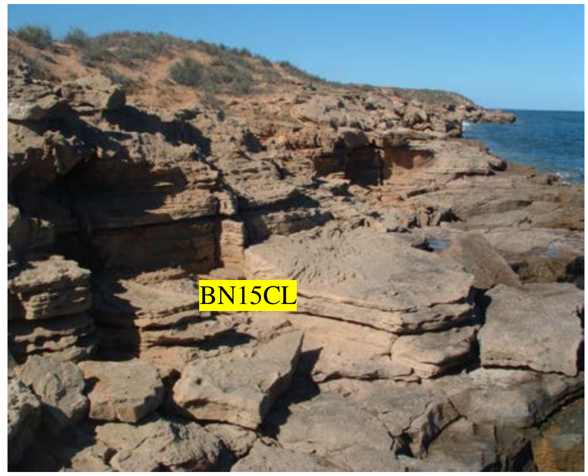
Constituents	Comments	%Total
Calcareous/Coralline Algae		30
Molluscs		20
Forams		10
Echinoid spines		10
Lithoclasts		10
Coral		5
Bryozoans		5
Quartz		5
Cement	Fibrous incipient aragonite	5

Interpretation: Lagoonal sand sheet/beach (grainstone) deposit, horizontal facies above of the Last Interglacial Reef.

Remarks: Extensively broken up into slab like pieces by high energy events (e.g. cyclones).

Specimen Number: BN15CL

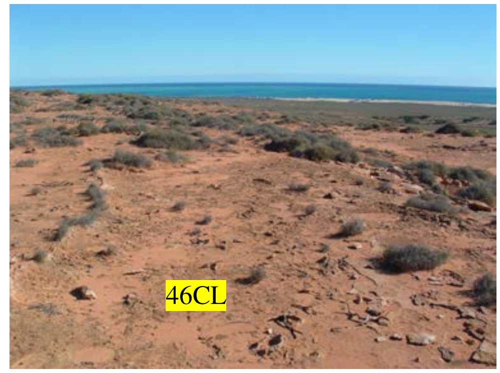
Location description..	Cliff coast in southern Area X.
Colour………………	Cream to pale grey
Unit…………………	Bundera Coralline Algal Limestone
Structure…………….	Very uniform fine Laminations that are slightly inclined. Contains oblique foresets
Approximate age……	Pleistocene
Grain size…………...	Fine to very coarse
Grain sorting………..	Good
Grain roundness...…..	Subrounded to rounded
Porosity…………......	Medium
Topography……...….	Low lying cliffs
Stratigraphy…...…….	Red Pleistocene dunes and parabolic dunes overly this unit.



Constituents	Comments	%Total
Calcareous/Coralline Algae		45
Molluscs		17
Forams		10
Echinoid spines		8
Bryozoans		7
Lithoclasts		6
Quartz		4
Cement		3

Remarks: Shelley layers (as visible in the above photo) are due to deflation lags at the time of deposition. Grains are horizontally aligned

Specimen Number: 46CL



Location description.. Inland region of the coast adjacent to Ningaloo coast.

Colour……………… Red

Unit………………… Longitudinal dunes and sand sheet

Structure……………. Unlithified sand

Approximate age…… Pleistocene

Grain size…………... Very fine to fine

Grain sorting……….. Poor

Grain roundness...….. Subrounded

Porosity…………...... Unlithified

Topography……...…. Linear formed longitudinal dunes and flat sand plain

Stratigraphy…...……. Acts as a covering unit, burying much of the Bundera & Trealla Limestone

Constituents	Comments	%Total
Quartz		90
Carbonate		8
K-feldspar	Twinning visible	2

Interpretation: Red clays have coated the grains giving the unit a rich red colour. A clean aronite sand.

Remarks: The most extensive unit in the Gascoyne region

Specimen Number: NB22CL

Location description..	Barred creek mouth at oceans edge (077967, 7393859) in Area Y
Colour………………	Cream
Unit…………………	Bundera Limestone (Pebbly)
Structure…………….	Crystalline foraminiferal packstone, bioclastic rudstone and quartz skeletal grainstone. Minor channelling and cross-bedding present.
Approximate age……	Pleistocene
Grain size…………...	Medium
Grain sorting………..	Well sorted
Grain roundness...…..	Angular to rounded
Porosity…………......	Poor
Topography……...….	30 m of outcrop with a North-South trend 10º seaward dip. Located where a major drainage network meets the ocean
Stratigraphy…...…….	Located between a permanent water body and the ocean.

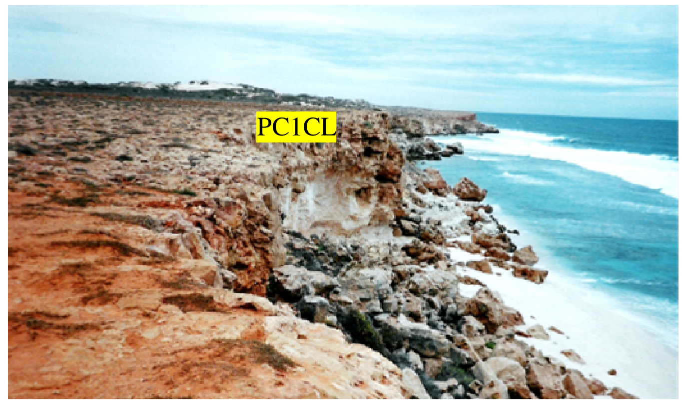
Constituents	Comments	%Total
Calcareous/Coralline Algae		52
Quartz		12
Cement	Whisker cements bind the grains together	10
Lithoclasts		8
Molluscs	Mainly bivalves	7
Forams		5
Coral		5
K-feldspar		1

Interpretation: Quartz skeletal grainstone with repeated pebble rudstone horizons. Floods plus high energy events have brought the pebbles to accumulate at the river mouth.

Remarks: Large pebbles (up to 25 cm) are well rounded and have been reworked in the marine environment (river) and during transport to the river. The pebbles are dense derived from the Giralia range.

Specimen Number: PC1CL

Location description..	Weathered surface of Trealla Limestone cliff (between Three Mile Camp and Red Bluff).
Colour………………	Cream with orange pisoliths
Unit…………………	Weathered surface of Trealla
Structure…………….	Pisolitic
Approximate age……	Tertiary
Grain size…………...	Very fine
Grain sorting………..	Moderate
Grain roundness...…..	Sub angular
Porosity……………......	5%
Topography……...….	Surface of high Coastal cliffs
Stratigraphy…...…….	Weathering effect of Trealla Limestone.



Constituents	Comments	%Total
Calcium carbonate		75
Quartz		15
Iron oxides	Occurs in concentric rings and linear laminations	10

Interpretation: Pisolite zone has developed in the phreatic/vadose transition zone. Circular and laminar iron oxide pisolites are present, indicative of a fluctuating water table.

Specimen Number : TB28CL

Location description..	Three Mile Camp
Colour………………	Cream to white
Unit…………………	Tantabiddi Rudstone
Structure…………….	The organisms have bound the stone together.
Approximate age……	125k
Grain size…………...	Coarse
Grain sorting………..	Poor
Grain roundness...…..	Poor
Porosity…………......	High
Topography……...….	Formed/preserved in an embayment
Stratigraphy…...…….	The Tantabiddi rudstone is representative the Last Interglacial Reef. It partially overlies the Bundera Calcarenite at several localities in Area Y, indicating it is younger in age to that particular Bundera unit.

Constituents	Comments	%Total
Calcareous/Coralline Algae		38
Molluscs	Bivalves form large constituent	20
Forams	Encrusting characteristics	17
Coral		15
Cement	Predominantly aragonite	5
Lithoclasts		3
Bryozoans		2

Interpretation: Clastic texture. The above organisms have bound the stone together

Remarks: Pristine example of Last Interglacial Reef, very well preserved.

Specimen Number : DB55CL

Location description.. Deflation Basin

Colour……………… Cream to white

Unit………………… Deflation Basin

Structure……………. Weakly lithofied

Approximate age…… Holocene

Grain size…………... Fine to medium

Grain sorting……….. Poor

Grain roundness...….. Well rounded

Porosity…………...... Medium ≈10%

Topography……..….. Barren flat topography between dunes.

Stratigraphy…...……. Between parabolic dunes

Constituents	Comments	%Total
Calcareous/Coralline Algae		59
Molluscs		14
Echinoid spines		8
Forams		6
Bryozoans		5
Quartz		4
Lithoclasts	Contain trace amounts of micrite cement	4
Cement	Micrite	1

Remarks: Partially lithofied.

5. Contents of accompanying CD rom.

Diss CD\GIS data (all raw GIS data)

Diss CD\GIS data\Geology and geomorphic units

Diss CD\GIS data\Geology and geomorphic units \X

Diss CD\GIS data\Geology and geomorphic units \Y

Diss CD\GIS data\Spatial analysis

Diss CD\GIS data\ Spatial analysis\Risk areas

Diss CD\GIS data\Access

Diss CD\GIS data \Access\X

Diss CD\GIS data \Access\Y

Diss CD\GIS data\Aerial Photographs (JPEG's **(reduced quality/size air photos of Areas X & Y)**

Diss CD\PDF Maps **(digital version of maps)**