Curtin University of Technology

Quaternary Geological Processes and Natural Resource Management of the Coastal Plain adjacent to Northern Ningaloo Marine Park

by

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ABSTRACT

The northern area of Ningaloo Marine Park incorporates a 40 m strip inland of the modern shoreline along Cape Range Peninsula. The reef forms a segmented barrier off the coast, controlling oceanic processes and related coastal evolution.

The Tertiary Cape Range Anticline extends along the central region of the peninsula, expressing past tectonism as a series of emergent terraces on the western flank.

The area has been relatively tectonically stable since the Last Interglacial, peaking between 121 and 128 ka BP. Reefs colonised Tertiary limestone at this time and form the foundation of the modern coastal plain, influencing its morphologic development.

Climate and related eustatic fluctuations since the Late Pleistocene are primarily responsible for the geologic and geomorphologic development of the coastal plain, with 6 distinct stages recognised as dominant controls in evolution. These stages are; 1) The Last Interglacial highstand 2) a related second phase of Interglacial highstand (?118 ka BP); 3) an overall regressive phase lasting from 118 to 30 ka BP; 4) a glacial peak and lowstand between 20 and 30 ka BP; 5) transgression to a highstand at 5.3 ka BP, and, 6) a regressive phase to the present.

GIS analysis of spatial variations in substrate and geomorphology enabled delineation of zones at risk of degradation from anthropogenic activities. It is evident that the majority of current coastal tourism access nodes are at high risk of degradation and careful land use planning is essential to ensure sustainability of tourism in these areas.

Furthermore, storm surge associated with tropical cyclones, tsunamis and potential sea level rise are capable of impacting low relief coastal areas and it is vital that these hazards be considered in future planning for projected tourism increases in the region.

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1 INTRODUCTION

Northern Ningaloo Marine Park is situated adjacent to the western and northern coastal plain of Cape Range Peninsula, in the north west of Australia, between 22°30'S and 21°45'S. The environmental value of this area has been recognised by the development of the Ningaloo Marine Park and Cape Range National Park (Figure 1.1).

The area is characterised by a series of emergent terraces representative of palaeo-reef systems, of which the lowest terrace defines the modern coastal plain foundation. Late Pleistocene and Holocene aeolian and marine sediment deposition upon this unit characterises the coastal plain lithology and morphology. The primary feature of the adjacent marine environment is the segmented, 280 km long fringing Ningaloo Reef, formed up to 3 km offshore as a modern analogue of palaeo-reefs (Hearn *et al*, 1986).

The unique landscape of the region has recently been recognised by the tourism industry and as land use magnitude is substantially increasing, government agencies are faced with the task of developing sustainable management strategies (Western Australian Planning Commission, 2004).

A sound knowledge of substrate characteristics and geomorphology is required in order to understand the potential risk of degradation due to land use. Furthermore, recognition of the terrestrial impacts of natural hazards is vital in the determination of sustainable access node placement. This study is intended to provide government agencies with a database to aid in regional natural resource management.

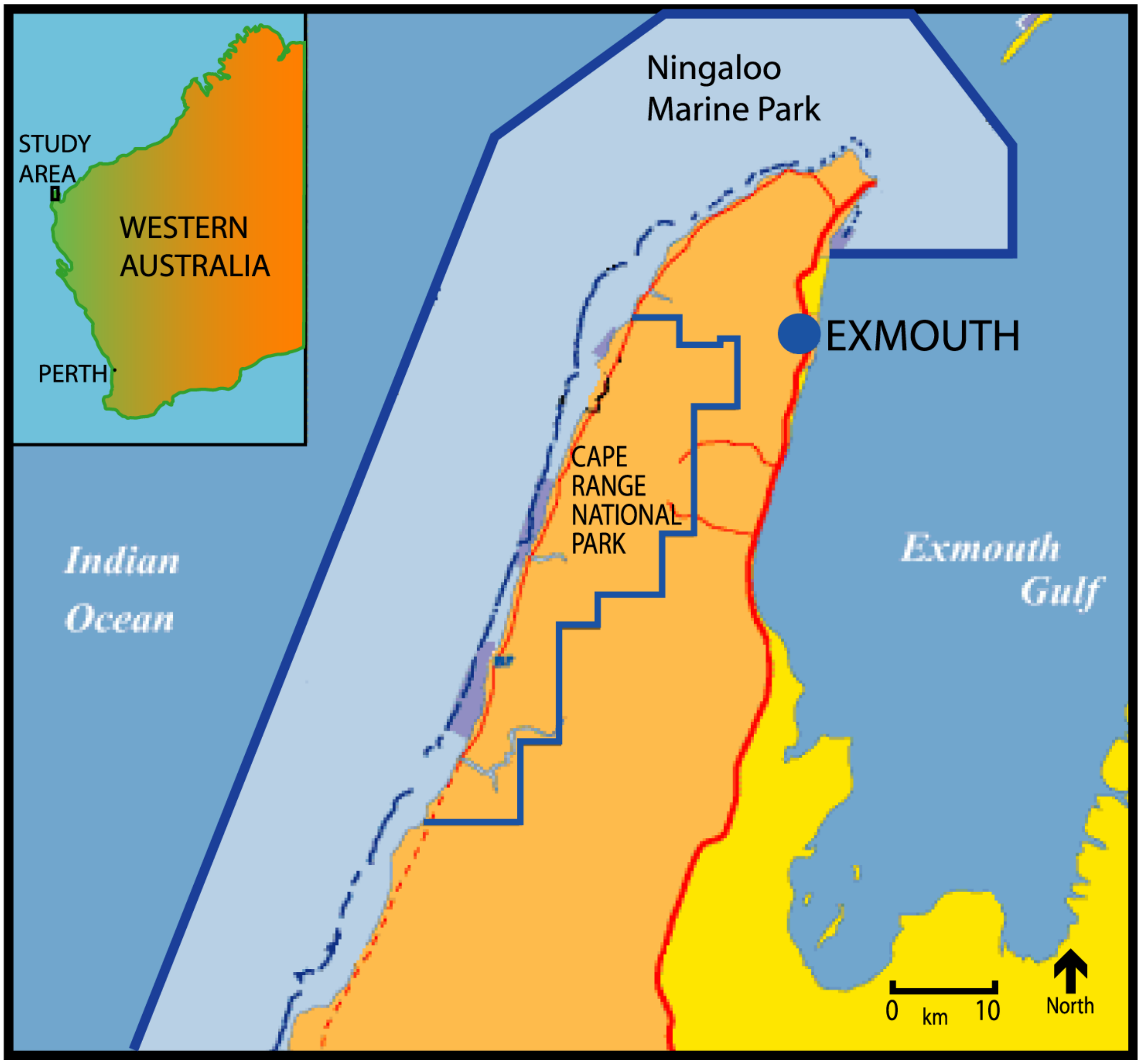


Figure 1.1 Location map of Cape Range Peninsula, Ningaloo Marine Park and Cape Range National Park, Western Australia (from Department of Fisheries, 2003).

1.1 Aims and Scope

The primary objective of this study is to evaluate the geology, geomorphology and physical processes in the north and western region of Cape Range Peninsula to provide a database and framework for assessment of degradation risks in the vicinity of tourism activity nodes.

Specific aims enabling the desired outcomes include;

- Analysis of regional geology and physiography to gain an understanding of the relationship between the wider region and the study area;
- Description of climatic and oceanographic processes, to characterise coastal geologic and geomorphologic responses;
- Digital mapping of the coastal plain and hinterland of the adjacent Cape Range Anticline in a Geographic Information System (GIS) format to delineate the spatial layout of lithology and geomorphologic features.
- To utilise GIS to document substrate characteristics[1] and distinguish spatial variations in capacity to withstand natural and anthropogenic impacts;
- To map nodes of land use and delineate potential impacts on substrate;
- To combine the outcomes of substrate and land use mapping to develop a model using GIS that demarcates regions at potential risk of degradation, and
- To use a digital elevation model to map coastal topography in the vicinity of major activity nodes and to make a preliminary assessment of degradation risk due to tropical cyclones, tsunamis and projected sea level rise.

[1] Substrate characteristics are defined in terms of constituents, consolidation, slope, vegetation cover and runoff potential, the overall capacity of a geologic or geomorphic unit to withstand change based upon these variables is defined as “substrate capacity”

1.2 Previous Work

Extensive research regarding the regional geology of the Cape Range area has been conducted since 1953, when West Australian Petroleum Pty Ltd (Wapet) first struck oil.

Condon (1954) and McWhae *et al*. (1958) initially documented the regional stratigraphy of the area. Condon (1965, 1967 and 1968) further published three bulletins describing stratigraphy in more detail for The Bureau of Mineral Resources.

van de Graaf *et al.* (1976) described the tectonic history and lithology of the area in production of the 1:250,000 Yanrey – Ningaloo map. Hocking *et al.* (1987) further delineated these features in a geological study of the entire Carnarvon Basin. More recent investigations regarding the tectonic history of the area have been completed by Malcolm *et al*. (1991) and Etheridge *et al.* (1991).

Geomorphology and Late Cainozoic geological evolution of the Cape Range has been documented by various authors and summarised by Wyrwoll *et al*. (1992).

Bryant and Nott (2001), Nott and Bryant (2003) and Kelletat and Scheffers (2003) have developed preliminary theories on tsunami impacts in the region.

Geology, geomorphology and land use extending 170 km to the south of the Cape Range Peninsula have been documented in a GIS framework by Blackwell (2002) and Leeden (2003).

1.3 Research Methodology

1.3.1 Reconnaissance

Initial determination of the extents of the study region involved analysis of areas adjacent to Ningaloo Marine Park that have not previously been geologically mapped and documented in a GIS format and are subject to projected increased land use. Based upon these criteria, Northern Winderabandi Point and Bundegi Sanctuary Zone were respectively chosen as the southern and northern boundaries.

Four distinct management regions exist in the area, each subject to different land use regulations. Therefore, further division of this area into four zones was deemed the most suitable way to assist in management. A large portion of the northern area of Cape Range Peninsula is administered by the Federal government for defence purposes, and as such is neither accessible to the public, nor available for land use study due to security restrictions. This inaccessibility resulted in geological mapping principally being accomplished through photo interpretation and the land use impacts not being analysed.

The four study zones chosen for analysis have been classified as;

- Bundera Coastal Protection Area (Area E),
- Coastal Cape Range National Park (Area F)
- Jurabi Coastal Park. (Area G)
- Northern Cape (Area H)

These areas and major landmarks are defined in Figure 1.2.

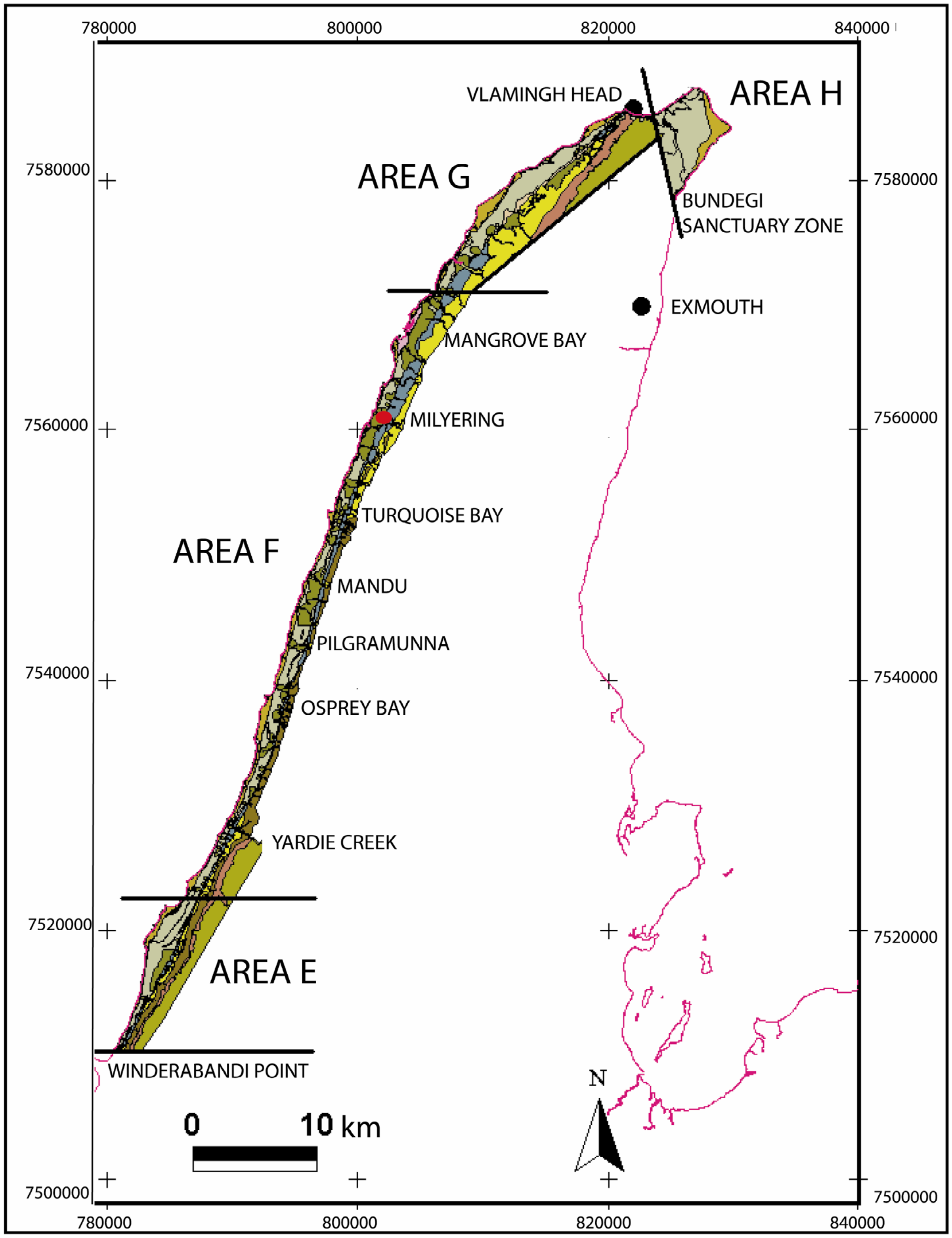


Figure 1.2 Location of mapped areas E, F, G and H.

The following photos were utilised, in hard copy format, for detailed air photo interpretation of geological and geomorphologic units and activity node locations.

Area E - Film WA4945(C) (Run28_5097-5099, Run 29_5091-5094) 07/07/03.

Area F - Film WA2764(C) (Run 4_5142-5171, Run 3_5138-5141) 12/08/89, Film WA4945(C) (Run 27_5109, 5118) 07/07/03.

Area G – Film WA2764(C) (Run 3_5134-5141, Run 2_5019-5133) 12/08/89, Film WA4945(C) (Run 22_5159-5162, Run 24_5149-5150) 07/0703.

Area H – Film WA 4945(C) (Run 22_5159-5162, Run 24_5149,5150) 08/07/03.

Regional characteristics were determined through use of Landsat and ASTER imagery in conjunction with the 1:250,000 Yanrey-Ningaloo and Onslow map sheets produced by the Geological Survey of Western Australia (1987).

1.3.2 Fieldwork

Fieldwork was conducted over a period of twenty days to ground truth and map the geology, geomorphology and activity nodes previously interpreted from aerial photography, and to further assess substrate capacity.

Stratigraphy was documented through analysis of terrace scarps, road cuttings and shallow trenches. Substrate and characteristic vegetation were collected and described for each geological unit. Further documentation of consolidation, topography, unit thickness, run-off potential and primary erosion sources was completed to enable the analysis of spatial variations in substrate capacity.

Ground traverses from low tide to the first terrace scarp were carried out in all accessible locations to document different stages of landscape evolution and associated spatial layout.

The magnitude of degradation in the vicinity of access tracks, campsites and car parks was documented to develop a model to delineate the extent of land use impacts.

Coastal topography surrounding day use and campsites was documented for the purpose of modelling degradation risk due to natural processes.

GPS locations were taken frequently and verified with a projected digital image to ensure mapping accuracy

1.3.3 Classification and Terminology

Development of nomenclature and descriptive methods was carried out with management concerns in mind. As land use activities are primarily tourism based, impacts due to the various activities associated with this industry have been focused on in definition of potential anthropogenic related degradation.

For the purpose of assisting managers in the development of sustainable land use regimes, it was deemed necessary to add further information to standard geological descriptions by describing the surficial attributes of each type of substrate, vegetation and land use magnitude. This served to emphasize the interconnectivity of dominant natural resources.

The term “Land Unit” has been used to define this descriptive regime. This terminology was modified from Zonneveld (1989) and Choudhury and Jansen’s (1998) use of the term. Thus “land unit” now defines specific properties of land using a multidisciplinary approach to account for overall geologic, geomorphic and vegetation characteristics. This results in a more comprehensive understanding of spatial variations in assessment of potential degradation due to land use.

The term Substrate Capacity has been modified after Land Assessment (1997), Blackwell (2002) and Leeden (2003) to enhance descriptions of land units by emphasizing the interconnectivity of lithology, consolidation, unit thickness, vegetation coverage and type, slope and runoff potential. Combined assessment of these features is intended to define a unit’s capacity to withstand impacts from natural or anthropogenic sources. A scale of 1-5 is used to assign a substrate capacity index (SCI) to each unit based upon qualitative assessment of predominant unit characteristics (Table 1.1).

Table 1.1 Unit characteristics used to classify substrate capacity index (SCI) for land units (modified after Land Assessment, 1997; Blackwell, 2002; Leeden, 2003).

SCI	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Consolidation/ Constituents	- Completely unconsolidated - Predominantly mobile calcareous sands	- Unconsolidated to poorly consolidated - Predominantly calcareous sands and channel conglomerate undergoing modern lithification	- Poorly to moderately consolidated - Predominantly compacted calcareous sands, clayey sands, silts and clays	- Moderately consolidated to well consolidated - Predominantly compacted calcareous sands and conglomerate	- Well consolidated - Predominantly limestone (recrystallised or calcretised) and conglomerate
Slope	Very steep to cliff > 45°	Moderate to steep 30-45°	Moderate 10-30°	Moderate to shallow 5-10°	Gentle – level <5°
Unit Thickness (Depth to Limestone Base)	> 5 m of unconsolidated material	> 5 m of poorly consolidated material	0.1 -5 m of moderately consolidated material	0.1 –5 m of well consolidated material	Exposed limestone
Vegetation Coverage and Type	- None to very sparse - Shallow rooted, low grassland	- Sparse - Shallow rooted grassland and low scrubland	- Moderate - Grassland with presence of low scrubland and acacias	- Moderate to high - Scrubland and acacias with low grassland	- High - Established acacias, high scrubland, and grasses
Runoff Potential	Very low	Low	Moderate	High	Very high

1.3.4 GIS Mapping

Arcview 3.2 GIS software was used to produce and represent geology, substrate capacity and tourism node maps.

This process involved the transferral of boundaries determined in the field and through interpretation work onto a digital ortho rectified air photo mosaic with a ground resolution of 1.4 m supplied by the Department of Planning and Infrastructure. The scale used for digitizing varied from 1:500 to 1:2000.

Mapping of the spatial extent of potential degradation due to tourism related land use involved initial classification of access types and assessment of over 400 sites to determine an optimal impact extent. Based upon this analysis, 15 m envelopes were created around all activity nodes to represent the potential area affected by use. The Land use classification and envelope extent reasoning is discussed in Appendix 1.

1.3.5 GIS Land Use Risk Analysis

A risk assessment model to delineate the magnitude of potential impacts on land units in the vicinity of activity nodes has been modified after Geoscience Australia (2004) and Stephens *et al.* (2003), defined as follows;

Risk = Hazard + Exposure + Vulnerability.

- Hazard is defined as the land use type,
- Exposure is defined as the potential optimal area affected by use, and
- Vulnerability is defined by substrate capacity.

The aim of risk assessment is to determine the best strategies to mitigate impacts. This involves spatial analysis of each component and assessment of which variables can be changed to optimally reduce risk. Figure 1.3 illustrates this concept by representing each component as sides of a triangle, with total risk being the area.

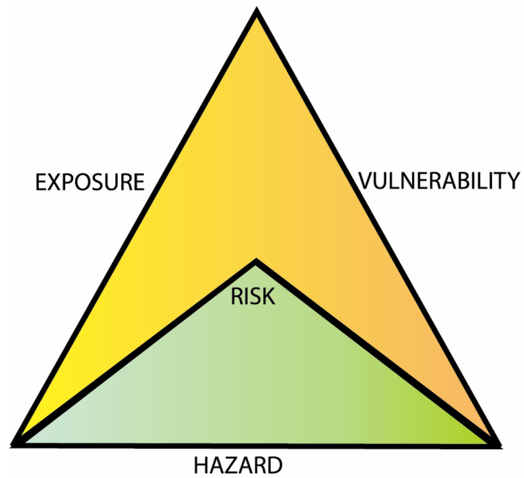


Figure 1.3 Risk model for hazards. Risk is represented by the area of the triangle and controlling variables by each side. The larger triangle portrays each variable as equal, the smaller triangle illustrates reduced risk due to exposure and vulnerability mitigation (after Geoscience Australia, 2004).

Arcview Spatial Analyst 1.1 software was used to delineate the combination of each component at any one location, which enabled assessment of potential degradation magnitude. The process involved conversion of conventional vector maps of substrate capacity (vulnerability), activity node extents (exposure) and type (hazard) into to raster (grid) format using a 5x5 m grid cell size. This process essentially turned initial maps into 25 m^2 cells with the characteristic substrate capacity and/or activity node in each defining the cell value. Grid cell size selection reasoning is outlined in Appendix 2.

Upon completion of grid creation, the SCI value, land use type and exposure of each cell was added together over the entire study region to define unique risk values for every 25 m^2 cell. The process of risk determination is further outlined in Figure 1.4 and the classification scheme used to categorise grid cells in Table 1.2.

Table 1.2 Degradation Risk Classification related to tourism based land use.

Risk Classification	Factors Controlling Classification
Extreme	Substrate Capacity 1 and two or more of the following - within bounds of access track, - within designated car park and - within designated campsite
Very High	Substrate Capacity 1 and one or more of the following; - within 15 m of access track, - within 15 m of designated car park and - within 15 m of designated campsite
High	Substrate Capacity 2 and one or more of the following; - within 15 m of access track, - within 15 m of car park and - within 15 m of campsite
Moderate	Substrate Capacity 3 and one or more of the following; - within 15 m of access track, - within 15 m of designated car park or - within 15 m of designated campsite
Low	Substrate Capacity 4 to 5 and one or more of the following; - within 15 m of access track - within 15 m of designated car park - within 15 m of designated campsite Also, all areas within bounds of sealed 2WD roads and no other activity nodes
Negligible	No current land use

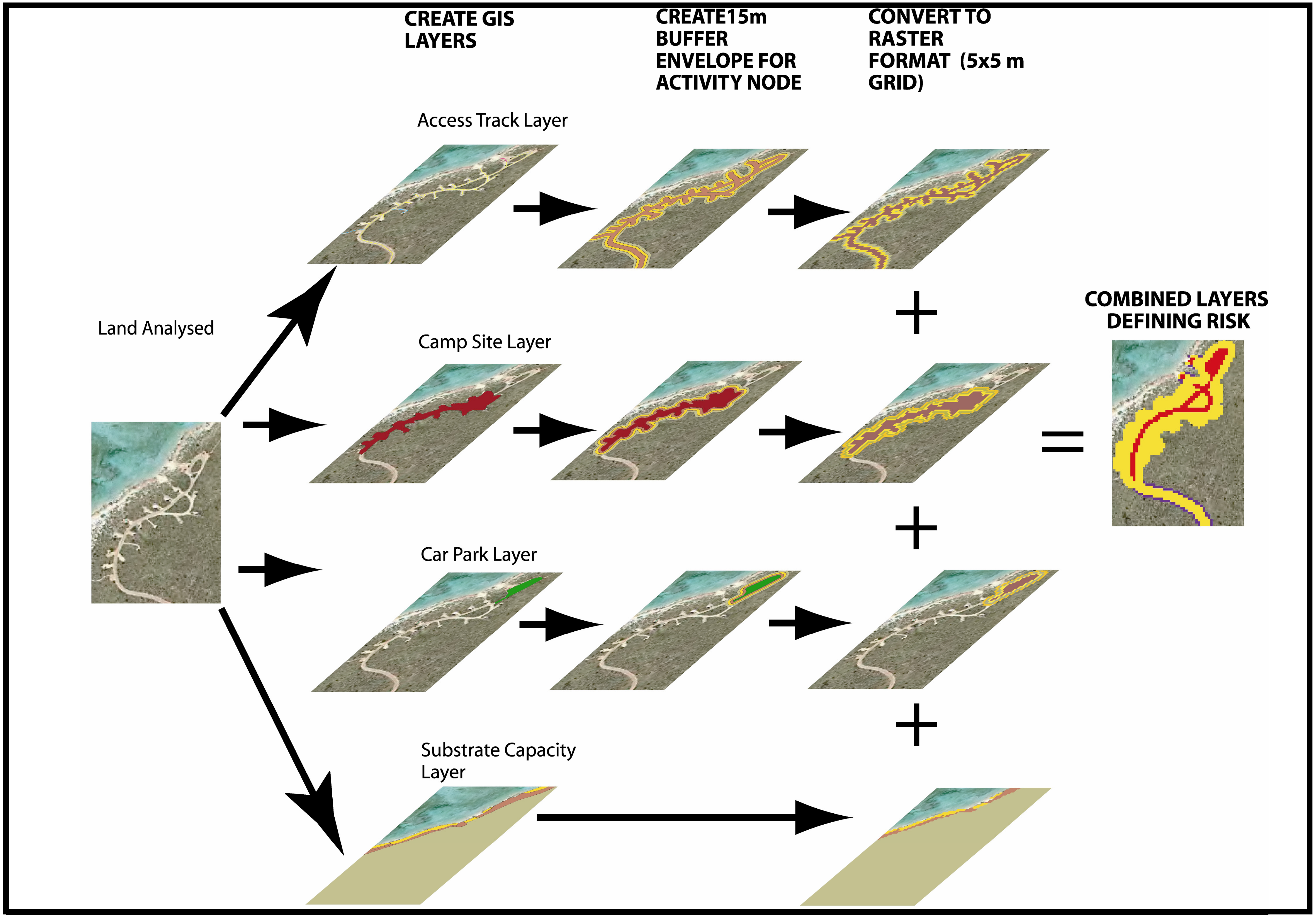


Figure 1.4 Risk analysis methodology in determining potential degradation of landscape as a result of land use.

1.3.6 Natural Hazard Classification

Based upon past records of natural hazard occurrence and future climate change models, natural hazards posing the most risk to tourism based activity node degradation have been classified as storm surge related to tropical cyclones, coastal inundation from tsunamis and projected sea level rise.

The model adopted to define risk associated with natural hazards is based upon the same concepts used in risk analysis due to land use as defined in 1.3.5, whereby risk is defined by the combination of exposure, vulnerability and hazard characteristics at specific locations (Geoscience Australia, 2004).

Exposure and hazard characteristics are the primary variables considered in risk analysis, as mitigation of degradation to access site infrastructure and landscape can be achieved to the highest degree through a firm understanding of these variables. Vulnerability is defined by an area's SCI and although this influences the magnitude of degradation to access sites, it is most relevant to minimise the potential to exposure and hence a model has been produced to delineate this variable.

The maximum potential properties of each hazard have been considered in risk analysis to enable optimal sustainability in resource management.

Exposure definition involved determination of topography using a digital elevation model accurate to 1 m to indicate spatial variability in potential terrestrial inundation based upon hazard classification.

Storm surge and sea level have been analysed according to the maximum sea level reached by each process and defined as being capable of inundating areas below this elevation. The reason for this assumption is that storm surge is essentially a prolonged rise is sea level that takes place over a period of hours, capable of inundating landscape below the level reached. Similarly, long-term sea level rise will effectively have the same impact in terms of terrestrial inundation.

Inundation of landscape by tsunamis occurs more rapidly and the associated kinetic energy of waves is capable of causing extensive inland inundation, essentially only alleviated through drag of the lower water layer upon the substrate (Gregson *et al.*, 1978). Therefore, in addition to wave magnitude, the surface roughness is considered the most important factor in determination of exposure.

The Natural Environment Research Council (2000) has defined the maximum inland extent of inundation, Xt, as;

$$X_t = \frac{0.06\,(H_0)^{4/3}}{(n)^2}$$

where; H_0 = Wave amplitude at shoreline
n = Manning's surface roughness coefficient

Considering n = 0.035 to 0.060 for ephemeral streams on plains with brush to low tree coverage, these values are classified as end members of surface roughness coefficients (Gardiner and Dackombe, 1983).

The process used to define tourism access nodes at most risk to degradation and the limitations in modeling are further described in Appendix 3.

1.3.7 Sample Preparation and Analysis

Thin sections, including grain mounts, were prepared by Curtin University Applied Geology Department. Grain mounts were prepared by loosely packing sediment, ensuring maximum preservation of original fabric, and bonding with epoxy resin. Slides were ground to 30 µm.

Samples from major units in the study region were analysed and descriptions of characteristics were made to delineate processes in substrate evolution.

1.3.8 Map Production

Geological units, trend lines, drainage, substrate capacity and the various types of access nodes have been mapped for the entire study region and presented in digital format on the accompanying CD. As the area of most interest to land managers is the Cape Range National Park, 8 geological maps of the coastal plain and the hinterland of the adjacent anticline have also been produced in hard copy at a scale of 1:15000, produced as Maps 1 and 2.

Based upon substrate capacity in the vicinity of access nodes, hard copy maps representing potential risk due to land use have been produced for all sites recognised by the Western Australian Planning Commission (2004) as major tourism nodes and presented on Maps 3 and 4.

2 REGIONAL GEOLOGY AND GEOMORPHOLOGY

2.1 Tectonic Framework

Cape Range Peninsula is situated in the onshore portion of the Mesozoic Exmouth Sub-basin, which defines the southern boundary of the Phanerozoic Northern Carnarvon Basin (Hocking *et al*., 1987; Malcolm *et al.*, 1991).

The Exmouth Sub-basin is bound to the east by the Rough Range, Bundegi and Learmonth Faults, to the west by the Cuvier Abyssal Plain and to the north by the Long Island Fault System (Figure 2.1) (Hocking *et al*., 1987; Malcolm *et al.*, 1991).

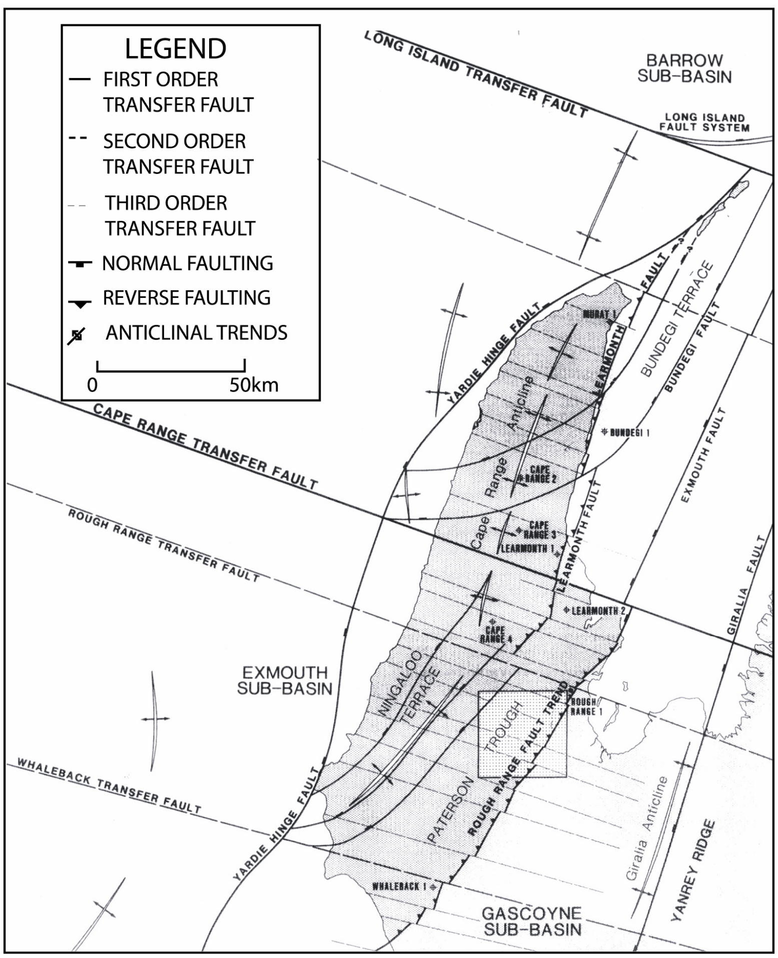


Figure 2.1 Tectonic elements of Cape Range and part of the Exmouth Sub-basin (after Malcolm *et al.*, 1991).

Five significant tectonic events have influenced the evolution of the Exmouth Sub-basin, which broadly correlate with the stages of development for the entire western and north-western margins of Australia (Veevers and Powell, 1984). These episodes are outlined in Table 2.1 and have been described in further detail by Malcolm *et al*. (1991)

Table 2.1 Summary of major tectonic events, Exmouth Sub-basin (from Malcolm *et al.*, 1991).

MAJOR TECTONIC EVENT	TIMING OF TECTONIC EVENT	PALYNOLOGICAL ZONE BOUNDARIES	SIGNIFICANCE OF TECTONIC EVENT	AFFECTED AREA	TYPE OF MOVEMENT	CHARACTERISTIC DEPOSITIONAL ENVIRONMENT IN EXMOUTH SUB-BASIN	COMMONLY USED FORMATION NAMES
5	MIOCENE		E-W COMPRESSIONAL EVENT ASSOCIATED WITH SUBDUCTION OF THE AUSTRALIAN PLATE BENEATH TIMOR.	ENTIRE WESTERN MARGIN OF AUSTRALIA. STRONGEST EFFECT IN THE NORTH WEST CAPE AREA.	REVERSE MOVEMENT ON PRE-EXISTING NORTHERLY TRENDING FAULTS, WITH UPLIFT AND EROSION. STRIKE-SLIP ON E-W TRENDING FAULTS.		
4	VALANGINIAN BERRIASIAN	S.aerolata E.torynum intra basal K.wisemaniae	COMPLETION OF BREAK-UP SECOND SYN-RIFT PULSE ONSET OF BREAK-UP.	MAJOR EFFECTS IN THE EXMOUTH SUB-BASIN.	AN EXTENSIONAL PULSE ASSOCIATED WITH LARGE FAULT THROWS, MASSIVE UPLIFT AND EROSION FOLLOWED BY A SAG PHASE IN THE EXMOUTH SUB-BASIN.	MARINE TRANSGRESSION DELTAIC NON-MARINE TO MARINE	WINNING GROUP BARROW GROUP WOGATTI SST., DUPUY SST. ANGEL SST. DINGO CLAYSTONE
3	OXFORDIAN CALLOVIAN	intra basal W.spectabilis intra lower W.digitata	COMPLETION OF BREAK-UP FIRST SYN-RIFT PULSE ONSET OF BREAK-UP	MAJOR EFFECTS NORTH OF THE EXMOUTH SUB-BASIN.	AN EXTENSIONAL PULSE ASSOCIATED WITH LARGE FAULT THROWS.	MARINE TO DELTAIC	
2	SINEMURIAN	intra C.torosa	RIFTING AS GREATER INDIA MOVED WESTWARD FROM THE AUSTRALIAN PLATE.	FORMATION OF THE EXMOUTH SUB-BASIN.	EXTENSIONAL MOVEMENT ALONG LOW ANGLE DETACHMENT FAULTS FORMING A GENTLE HALF-GRABEN BASIN SETTING.	MARGINAL MARINE TO NON-MARINE MARGINAL MARINE FLUVIO - DELTAIC	DINGO CLAYSTONE LEARMONTH FORMATION BRIGADIER FORMATION MUNGAROO FORMATION
1	LATE CARBONIFEROUS		RIFTING REPRESENTING THE ONSET OF FRACTURING OF GONDWANALAND TO FORM THE "WESTRALIAN SUPERBASIN."	ALONG THE ENTIRE WESTERN MARGIN OF AUSTRALIA.	A PERMIAN INTRACRATONIC DOWNWARP ASSOCIATED WITH SIGNIFICANT EXTENSION, BECOMING A SAG BASIN IN THE TRIASSIC WHEN EXTENSIONAL RATES SLOWED DOWN SIGNIFICANTLY.	SHALLOW MARINE SHALLOW MARINE SHELF GLACIAL SEDIMENTS	LOCKER SHALE KENNEDY GROUP BYRO GROUP WOORAMEL GROUP LYONS GROUP

The most important phase of activity that has defined the modern structural setting of the region took place in the Late Miocene. Reactivation styles during this period vary along the North West Shelf relative to the change in convergence angle around the margin, depending on the strike of the underlying reactivated structure (Etheridge *et al*., 1991).

The Cape Range and Rough Range Anticlines formed at this time through an east west phase of compression resulting in structural inversion and thrusting along the Learmonth and Rough Range Faults, respectively. The reason the anticlines exemplify the Miocene tectonic event so well appears to be related to the atypical low angle listric nature of the underlying faults at the basin margin, which maximised the uplift effect of lateral reverse movement (Figure 2.2) (Etheridge *et al*., 1991; Malcolm *et al*, 1991).

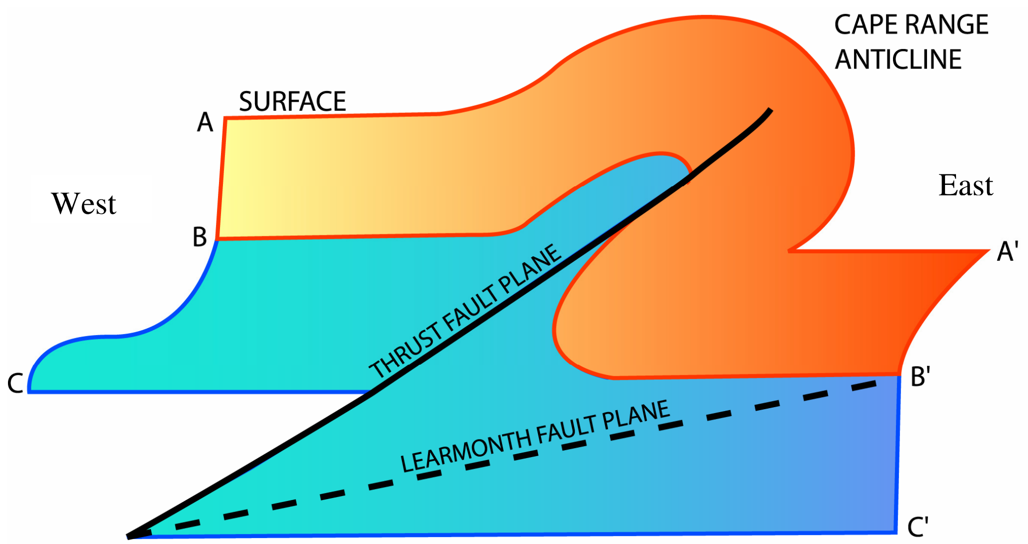


Figure 2.2 Interpreted mechanism for the formation of Cape Range Anticline as a blind thrust (modified after Malcolm *et al.*, 1991).

The amount and lateral extent of movement along the Learmonth Fault was greater than that of the Rough Range Fault, as demonstrated by the Cape Range Anticline having a vertical closure of 314 m in comparison to 60.7 m for the Rough Range anticline (Wyrwoll *et al*, 1992; Ellis and Jonasson, 2001).

Episodic uplift subsequent to the Late Miocene is exemplified by the existence of four distinct, emergent terraces discontinuously defining the western flank of Cape Range Anticline. Timing of tectonic activity is not known, as stratigraphic dating is not complete. However, the youngest terrace, dated at 118-130 Ka BP, does not show signs of deformation, indicating that episodic uplift continued into the Quaternary but has declined or ceased since this unit's deposition. (Kendrick *et al.*, 1991).

2.2 Regional Geomorphology

Cape Range Peninsula is situated in the physiographic region recognised by Hocking *et al*. (1987) as the Macleod Region, which extends 200 km to the south, terminating at the Gascoyne River. The dominant morphologic signature of the area has been defined 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 largest of these anticlinal domes is the Cape Range Anticline, which extends along the majority of the central region of the Cape Range Peninsula, absent only in the far north. This anticline trends north to northeast and extends 100 km north to south, reaching up to 20 km in width (Wyrwoll *et al.*, 1992).

The western flank of the anticline is characterized by a series of emergent terraces. These terraces provide a record of tectonic history, indicating a combination of episodic uplift and sea-level fluctuations. Van de Graaff *et al*. (1976) distinguished four erosional terraces; Tantabiddi, Jurabi, Milyering and Muiron. Each terrace is overlain by shallow marine, shoreline and aeolian sediments and truncated seaward by an erosional scarp, forming the corresponding members (Figure 2-3). (van de Graaff *et al.,* 1976).

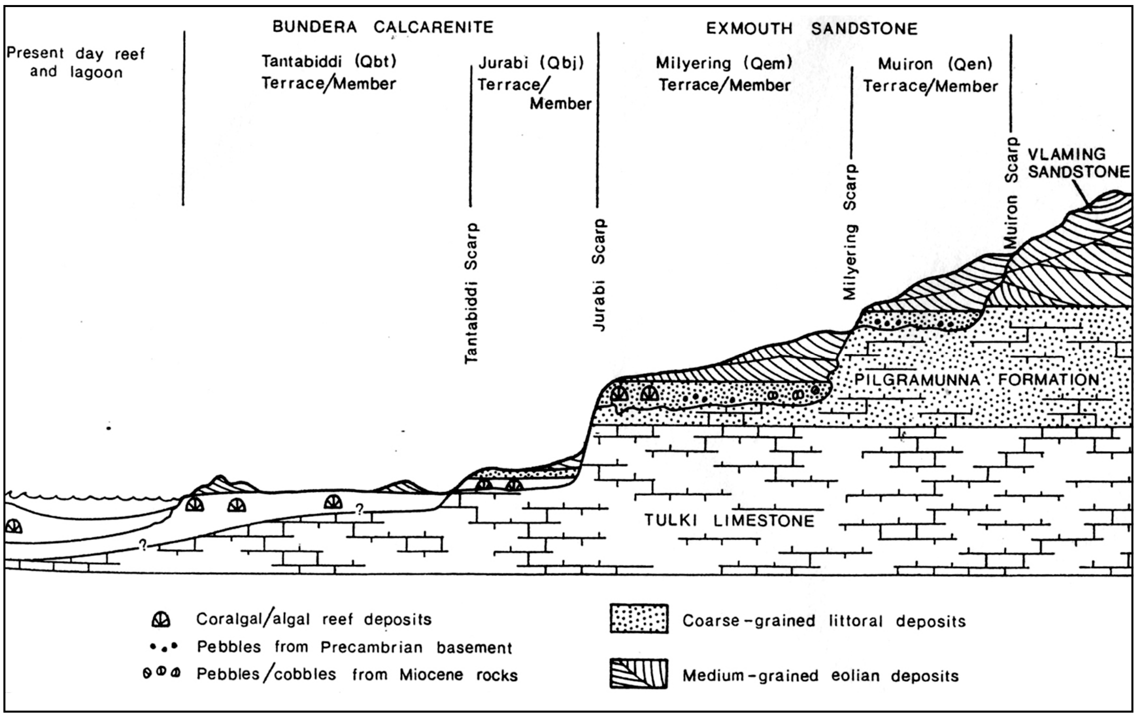


Figure 2.3 Morphology of the Pleistocene-Holocene coastal plain and Tertiary aged terraces to the east of the plain (from van de Graaf *et al.*, 1976).

The height above sea level of each terrace was measured in 8 locations along the range by Van de Graaf *et al*. (1976), the localities and corresponding elevations are outlined in Figure 2.4 and Table 2.2.

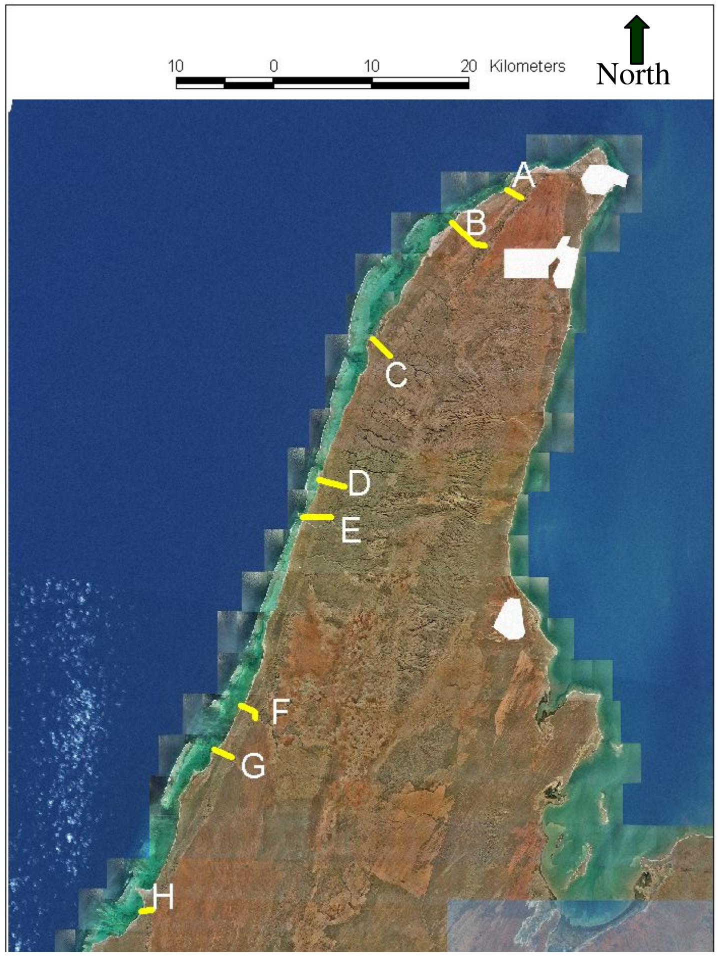


Figure 2.4 Locations of elevation measurements along Cape Range Peninsula (adapted from van de Graaf, *et al*., 1976).

Table 2.2 Elevation of Cape Range Terrace Members. Datum is mean low water springs level at Norwegian Bay. (modified after van de Graaf *et al*, 1976).

Terrace Members	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Pigramunna-Vlaming contact	52	74	a	78	73	95	76	72
Base of Pilgramunna	25	47	62	42	38	65	39.5	42
Upper Muiron contact	C	57.4	?48	57	61.6	58	55.8	62.5
Upper Milyering contact	19.8	33.3	31.4	46.6	42.1	?39.1	38.2	37.6
Upper Jurabi contact littoral/aeolian	c	10.3	a	c	?22	18.9	a	18
Jurabi base of littoral	c	8.8	9.1	19.5	17.9	15.2	12.8	14.3
Upper Tantabiddi sheetwash/reef contact	1.2	2.3	3.5	5.5	3-4	3	3-6	3-5
Lower Tantabiddi coralgal reef	c	2.3	c	5.5	c	c	c	c

c = concealed, a = absent, ?=level ±2 m (difficult to place in field), elevation in metres.

The three upper terraces are deeply dissected and associated alluvial fans have developed extensively upon the lowest terrace, which forms the foundation for the modern coastal plain (Wyrwoll *et a*l., 1992).

Sea level variations subsequent to the formation of the Tantabiddi Terrace are primarily responsible for evolution of all other geomorphologic features of the coastal plain. Longitudinal desert dunes characterise a large area in the north of the peninsula and landward of the anticline in the southern regions of the peninsula, forming in a lowstand period when sea level was –125 m (Wyrwoll *et a*l., 1992).

Beach ridges predominantly define the region ranging between 100 and 500 m from low tide, with the most landward ridge characterising the level of a marine highstand 5.3 Ka BP, and seaward prograding ridges represent regression since this time.

The offshore environment is dominated by the Ningaloo Reef, which is a modern analogue of adjacent palaeo-reefs, forming a shoreline parallel narrow reef crest and lagoonal environment up to 3 km wide (D'Adamo and Simpson, 2001). The reef dictates wind, wave and tidal currents within the lagoon that in turn control modern marine and terrestrial sedimentary systems, defining coastline morphology (Sanderson, 2000).

2.3 Cainozoic Geology

A 500 m thick sequence of Palaeocene-Miocene rocks, the Cape Range Group, form the core of the range. Up to 10,000 m of Phanerozoic rocks underlie this (Hocking, 1990). Members of this group in the region include; Mandu, Tulki and Trealla Limestones, Vlaming Sandstone, and the Pilgramunna Formation, these form a single, unconformity bounded, depositional unit in the Carnarvon Basin (Hocking *et al.*, 1987).

Quaternary sequences represent sedimentation subsequent to the Tertiary. The four emergent marine erosion terraces preserved on the western flank of the Cape Range Anticline are made up of the Exmouth Sandstone along the upper Muiron and Milyering Members and the Bundera Calcarenite along the lower Jurabi and Tantabiddi Members. Extensive areas to the northeast and south east of the range are expressed as low lying desert dune plains formed in the last Glacial Period 20 Ka BP.

The coastal plain is extensively covered by Late Pleistocene aged alluvium derived primarily from the Cape Range Group and Late Pleistocene to Holocene calcareous marine and aeolian sediments. Table 2.3 outlines the ages and major lithologic components of each unit. Further detail of Quaternary Units is provided in chapters 4, 5 and 6.

Table 2.3 Cainozoic geology of the Cape Range Peninsula (after Hocking *et al.*, 1987; Van de Graaf *et al.*, 1976)

Age	Formation	Thickness	Lithology	Comments
HOLOCENE	Various coastal plain units	<20 m	Aeolian deposits, alluvium, colluvium, littoral deposits. (Described in Detail in chapters 4, 5 and 6)	Predominantly unlithified carbonate sediments
PLEISTOCENE	LONGITUDINAL DUNES BUNDERA CALCARENITE - Tantabiddi Member - Aeolian Member - Mowbowra Conglomerate Member	<20 m	Longitudinal Dunes- Quartzose and calcareous calcretised poorly lithified sand Bundera Calcarenite Tantabiddi Member – Lower margins calcarenite and calcirudite with extensive coralgal framestone. Upper margins intertidal and lagoonal calcirudite and grainstone. Bundera Calcarenite Aeolian Member - Medium textured, rubified and moderately indurated calcarenite overlain by large-scale cross-bedded calcareous aeolian deposits. Large solution pipes penetrate this dunal deposit from a strong surface calcrete. Mowbowra Conglomerate – Limestone pebble conglomerate, well sorted calcarenite and minor coralgal reef deposits	- Aeolian Member age unknown, intertidal beach face overlain by foredune aeolian deposits. - Tantabiddi Member confined to shoreline platforms and minor outcrops on coastal plain - Mowbowra Conglomerate diachronous with modern channel deposits
PLIOCENE	BUNDERA CALCARENITE - Jurabi Member EXMOUTH SANDSTONE - Milyering and - Muiron Terrace Members	<20 m	Jurabi Member – Coralgal boundstone and grainstone Exmouth Sandstone - Milyering Member: Algal boundstone and conglomerate overlying and laterally grading into coarse grained to pebbly quartzose calcarentite with large scale, cross bedding. - Murion Terrace Member: Calcareous quartz arenite ranging from coarse grained sand to pebbly granule conglomerate grading upwards into a well-sorted, medium grained quartzose calcarenite.	All members dissected and discontinuously preserved. Milyering and Muiron Member: Basal margin formed in a littoral environment, grading upwards to an aeolian environment. Occasional shallow karst features
~~	~~~~~~~~~~~~	~~~~~~	~~~~~~~~~~~~~~~UNCONFORMITY~~~~~~~~~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~~~
MID-LATE MIOCENE	VLAMING SANDSTONE	~ 38-65 m	Calcarenite: well sorted, quartzose, Aeolian origin.	Crops out around Yardie Creek and the northern Cape
	PILGRAMUNNA FORMATION	~ 20-30 m	Calcarenite: well sorted, quartzose, fine-very coarse grained with interbedded beds of packstone and boundstone.	- Crops out in northern region of Cape Range Peninsula
	TREALLA LIMESTONE	~ 20 m	Relatively pure and commonly shelly, bioclastic packstone. Contains Banded dolomitic micrite interpreted as algal mat deposits	Outcrops negligible to absent in western margin of Cape Range
	TULKI LIMESTONE	~ 95 m	Coarse grained calcarenitic, muddy foraminiferal packstone and mud free grainstone locally associated with low angle cross bedding. Upper facies, massive recrystallised limestone.	Extensive outcrop where Pliocene Bundera Calcarenite, Exmouth Sandstone absent
	MANDU LIMESTONE	~ 278 m	Calcarenite/calcilutite/calcisiltite: chalky to marly fossiliferous, notable large Lepidocyclinid foraminifera.	Outcrops negligible to absent on western margin of Cape Range

3 PHYSICAL PROCESSES

3.1 Climate

Coastal processes and associated influences on landscape development can only be understood with a firm knowledge of palaeo and modern climate controls.

3.1.1 Quaternary climate and Eustacy

Cyclic changes in climate and sea level are known to have existed for at least the past 250 ka (Figure 3.1) (Wyrwoll, 1993; Chappell and Shackleton, 1986). However, the major fluctuations that have controlled coastal plain evolution of the Cape Range Peninsula have taken place since 128 Ka BP (Stirling *et al.*, 1998). Records of changes can be interpreted through analysis of preserved coral reef deposits and palynology. Analysis of corals involves interpretation of water temperatures to infer sea level at the time of growth. Assumption that environmental conditions for specific plant growth was analogous in the past to the present, palynological assessment of the pollen record through time reveals evidence of characteristic vegetation shifts representative of climate changes.

The most significant highstand of the Quaternary Period peaked between 128 and 121 Ka Bp. Coral and coralgal reef building commenced as a result of this event and Sr/Ca ratios from preserved *Porites* from Vlamingh Head, at the north of the peninsula, suggest sea level was +3 to 4 m and summer and winter temperatures respectively ranged from 23°C to 28°C and 23°C to 20°C. (McCulloch and Esat, 2000).

Kendrick *et al*. (1991) analysed corals from Pilgonaman Gorge and inferred a possible double peak in climatic maxima, with the major phase of warming being followed by a cooling trend and another warming episode at approximately 118 Ka BP. However, evidence of this phenomenon is not conclusive and further research is required to confirm or dismiss this theory.

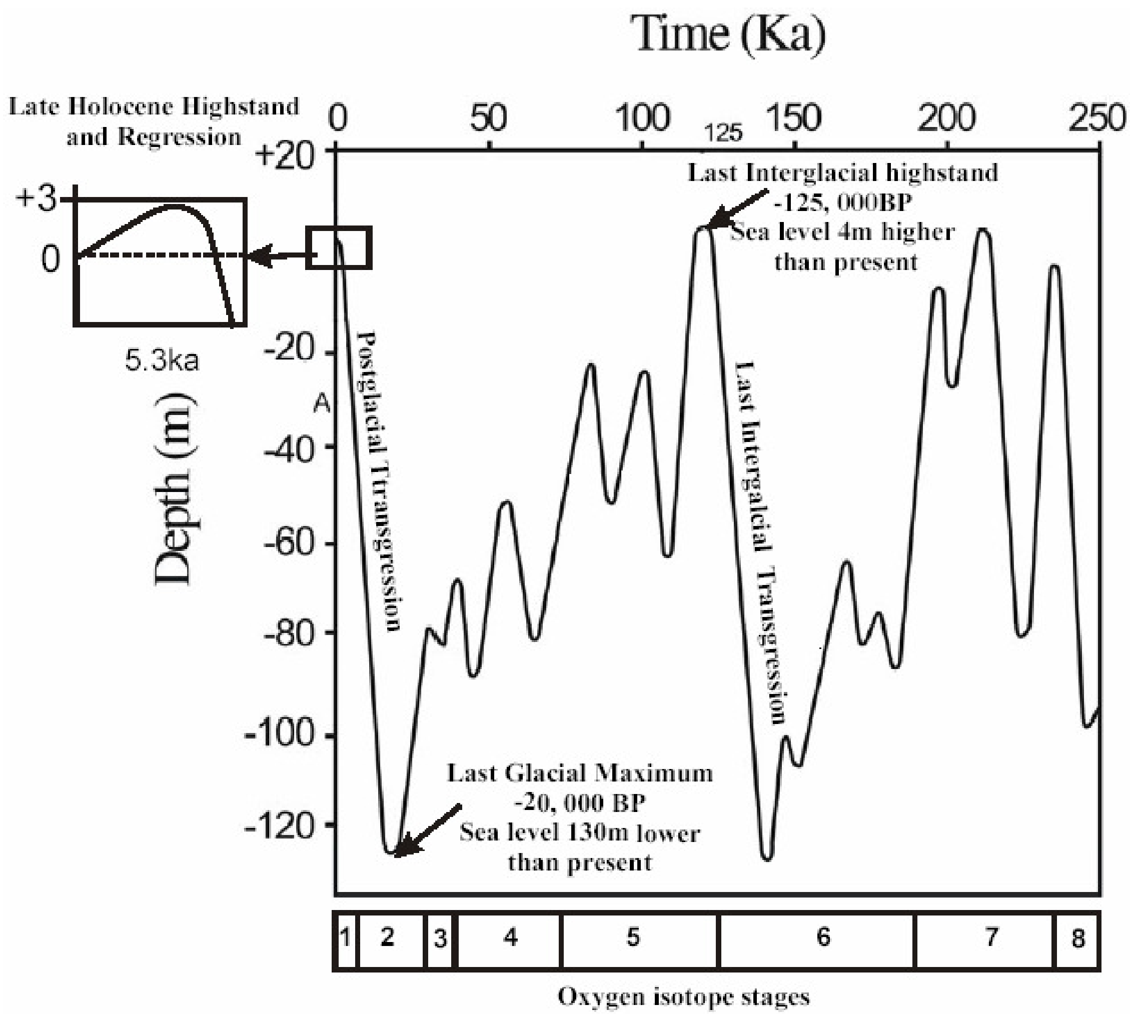


Figure 3.1 Eustatic Sea level variations. (after Chappell and Shackleton, 1986).

Van der Kaars and De dekker (2002) identified climatic flux subsequent to the Last Interglacial through palynological analysis of oceanic cores 60 km to the west of the Cape Range Peninsula. Results of these studies reveal that temporally variable cycles of arid and relatively tropical conditions have persisted for the past 100 ka.

The climate between 100 ka and 64 ka B.P was relatively humid, with annual rainfall of at least 300-400mm. Maximum summer rains, most likely related to increased Tropical Cyclone incidence, are evident at 100, 80 and 79 ka BP.

A hiatus from 64 ka to 46 ka BP prevents climatic inference through this period. However, subsequent to this time, pollen records suggest a shift towards aridity. Furthermore, evidence of a glacial period is recorded through the development of longitudinal dune fields in the northern and southern areas of the peninsula. Wyrwoll *et al.* (1992) obtained two thermoluminescence ages of 23.4±6.7 and 16±1.7 ka BP from dune sands in area G defining the timing of this event. Wyrwoll *et al.* (1992) determined that sea level was approximately 125-130m below the present height.

The cool, dry period was followed by a rapidly fluctuating climate until 12,370 ka BP, represented by high rates of vegetation change inferred from pollen records (Van Der Kaars and De dekker, 2002). However, the overall trend was towards climatic warming until 5.3 ka BP. At this time the climate reached the most recent warm, wet period. Mangrove habitation along the coast is representative of this event (Kendrick and Morse, 1990). Flooding of inland regions in various locations suggest sea level was +1-2 m.

Subsequent to this warmer climate, a regressive phase representing increasing aridity began and has continued to date.

3.1.2 Present Climate

The climate of the Cape Range Peninsula is hot arid, with relatively high temperatures, low rainfall and significant evaporation rates. Two distinct seasons exist; the hot summer spans from October to April and moderate winter from May to September. The mean annual rainfall and temperature ranges are illustrated in Figure 3.2.

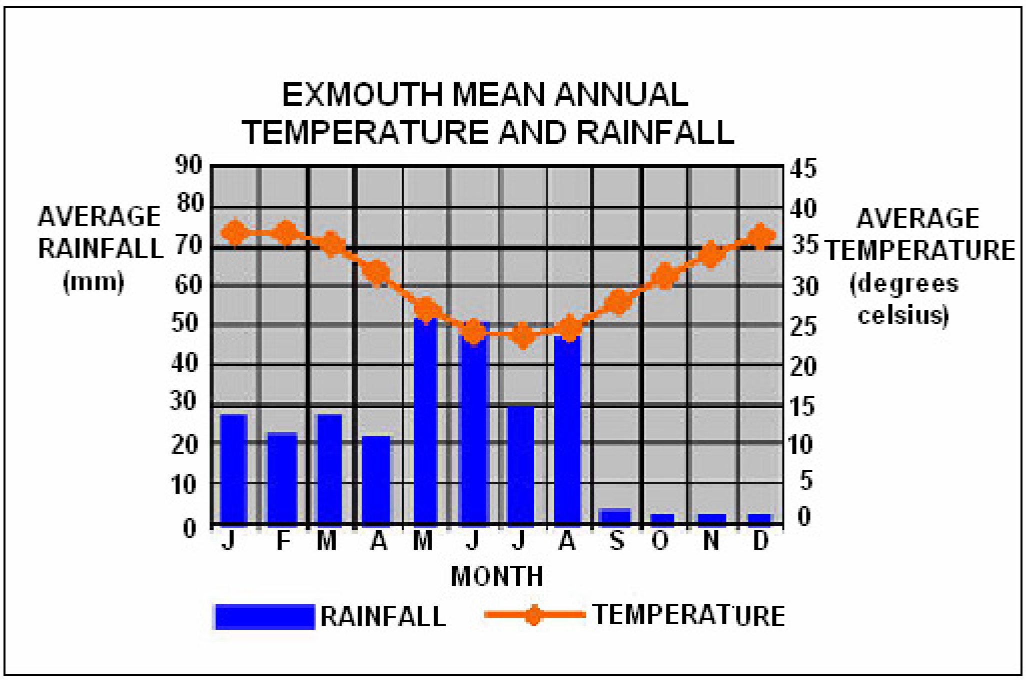


Figure 3.2 Mean annual variations in temperature and rainfall for Exmouth, 5 km south of study area H (from Bureau of Meteorology, 2003).

Rainfall differs up to 40% inter-annually averaging 200-300mm, and mean evaporation is 3137mm/year (Bureau of Meteorology, 1999; D'Adamo and Simpson, 2001).

Infrequent summer precipitation is commonly cyclone related, whereas early winter cloud bands account for over 80% of rainfall during this period (J. Courtney, pers. comm., 2004).

On a broad scale, prevailing wind patterns are controlled by the annual north-south movement of the high pressure belt systems circumnavigating the globe (D'Adamo and Simpson, 2001). In summer the belt moves southward, and monsoonal wind systems move into the area predominantly bringing southerly winds with slight variations to the east and west (Hearn *et al*., 1988). Greater variation in wind direction is evident in winter, with southerlies to south-easterlies most common (Sanderson, 1997). Temporal wind variability and persistence is detailed in Figure 3.3.

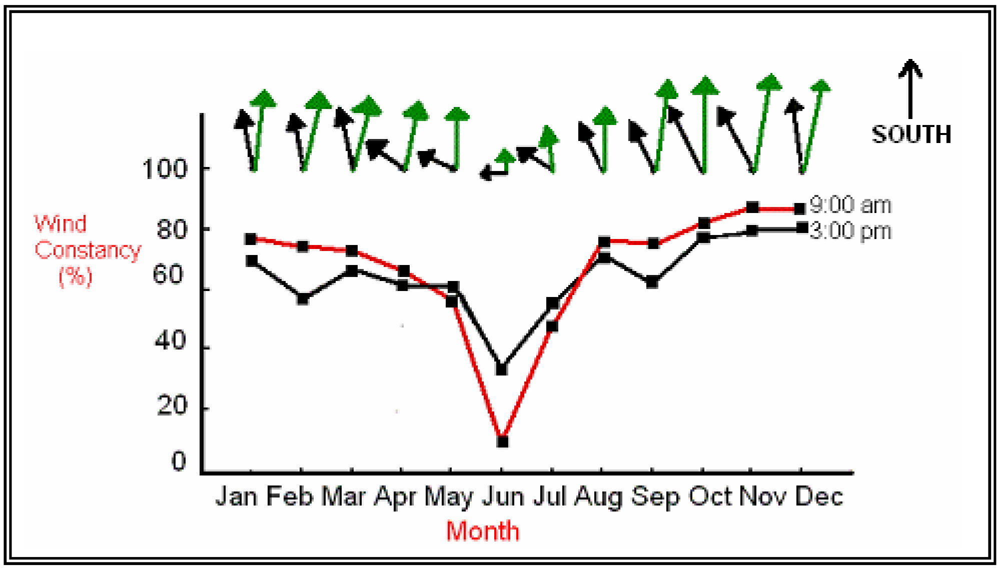


Figure 3.3 Monthly mean wind vectors along the Cape Range coast. Wind velocity is proportional to arrow length (black arrows: 9:00am, green arrows: 3:00pm) and wind constancy (persistence of the wind direction) (after Taylor and Pearce, 1999).

3.1.3 Tropical Cyclones

Tropical cyclones (TC's) are an important characteristic of the summer climate regime in the north west of Australia, passing the Cape Range every 2 to 3 years between December and March (Figure 3.4). Although the majority of TC's fall under the reasonably low impact categories of 1 or 2 in terms of magnitude, highly variable spatial and temporal properties for each event lead to spatially unpredictable rainfall, flooding, winds, storm surges and associated infrastructure damage (Table 3.1).

Origination of TC's is to the north of the region over warm oceanic waters subject to very low atmospheric pressure from solar heating. The movement of air to achieve pressure equilibrium is influenced by the Coriolis Force, developing a cyclonic wind system characterised by velocities 4 to 5 times greater than average (Collins *et al*, 1999). The system travels southwards, exposing the coast to northerly winds as the clockwise flow of air approaches the land (Figure 3.5).

Coastal impacts from TC's include; severe erosion of beaches, mobile dunes and blowouts, flooding and related erosion and sediment transport, potentially having effects that persist through typical quiescent periods (Sanderson, 1997)

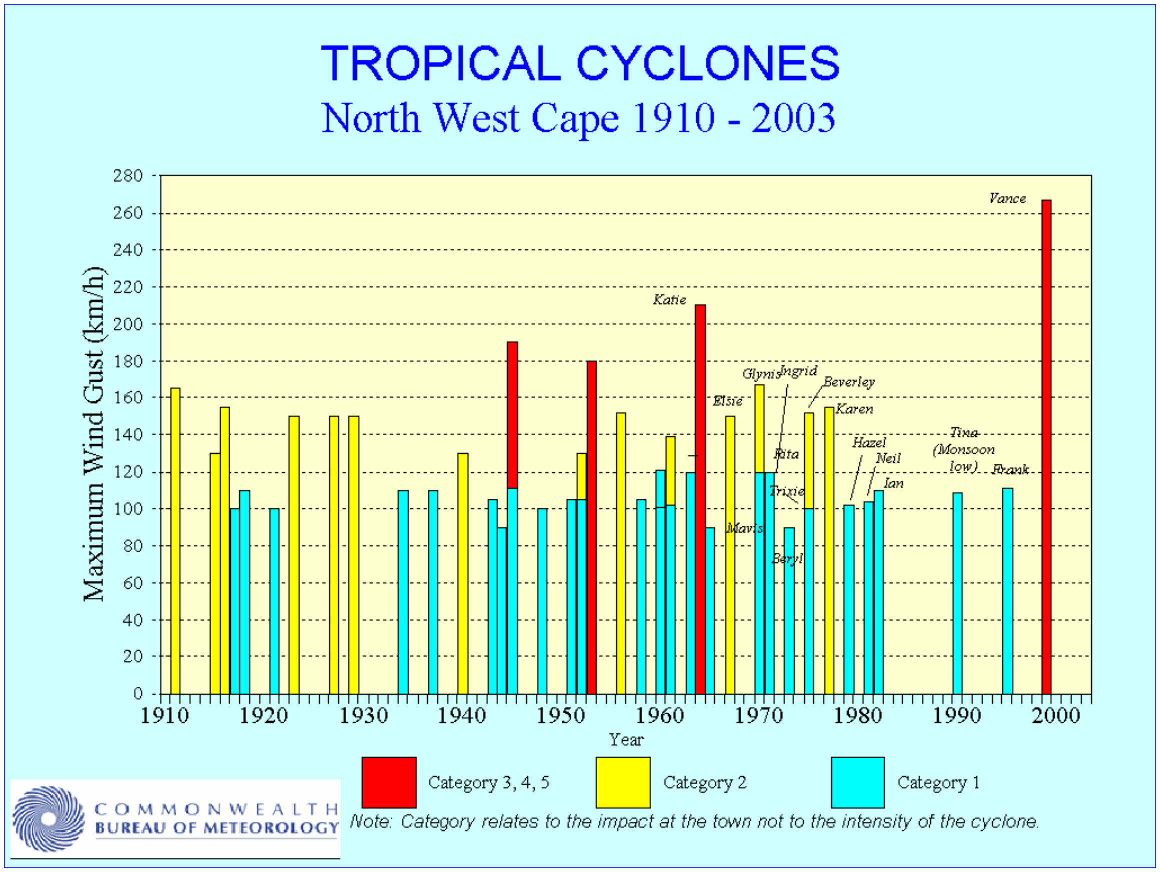


Figure 3.4 Magnitude and wind velocity associated with tropical cyclones passing the Cape Range Peninsula since 1910. (from Bureau of Meteorology, 2003).

Table 3.1 Tropical cyclone severity categories, typical wind and pressure characteristics and recorded occurrence (after Bureau of Meteorology, 1999).

Category	Average Wind Velocity (km/hr)	Peak Wind Velocity (km/hr)	Central Pressure (hpa)	Typical Effects	Recorded Occurrence: Learmonth (1910-1999)
1	63–90	<125	>985	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings.	22
2	90–120	125-170	985-970	Minor house damage. Significant damage to small-scale infrastructure. Risk of power failure.	10
3	120-160	170-225	970-945	Some roof and structural damage. Some caravans destroyed. Power failure likely,	2
4	160-200	225-280	945-920	Significant structural damage. Dangerous airborne debris. Widespread power failure	0
5	>200	>280	<920	Extremely dangerous with widespread destruction.	1

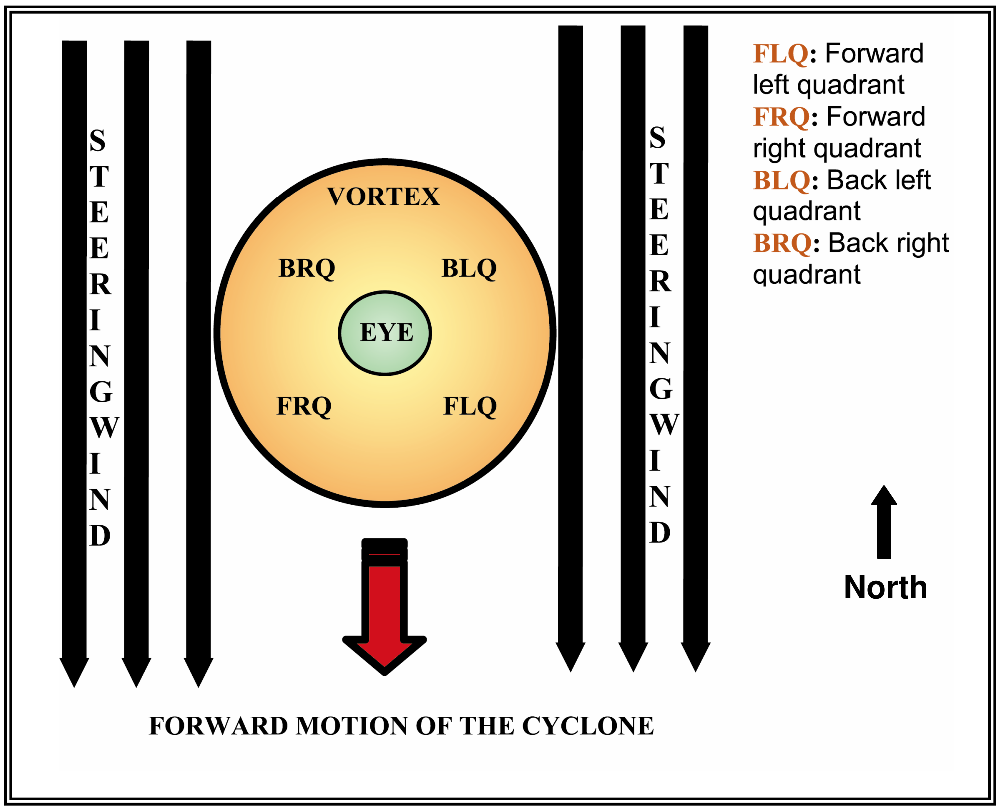


Figure 3.5 Generic model of a tropical cyclones (horizontal section) approach toward the coast. The region of strongest winds is in the forward left quadrant (adapted from Coch, 1994).

3.1.4 Climate Change Scenarios

Global temperature and sea level rises over the past century anomalous to the expected natural rates of change suggest anthropogenic-induced impacts on climate.

Mean global temperatures rose by 0.7°C in the twentieth century in comparison to an average of ±0.3°C (Church and Gregory, 2001). Furthermore, sea level rise over a 10 year period towards the end of the century of 2.4mm/year was much greater than preceding rates of 0.3 to 0.8mm/year (Hardy, 2003).

The proportion of climatic variation able to be attributed to human activity cannot be resolved with certainty. However, it is evident that an unnatural overprint is taking place and assumption that this trend will continue enables development of sustainable management strategies to account for possible climatic shifts and related sea level rise.

Based upon climatic trends of the twentieth century, The Intergovernmental Panel on Climate Change (IPCC) (1996) has developed global models to predict future temperature changes likely to take place over the next century (Figure 3.6). The CSIRO (2001) has further delineated likely influences for climatically correlative regions in Australia, outlining predicted temperature changes by 2030 and 2070 (Figure 3.7).

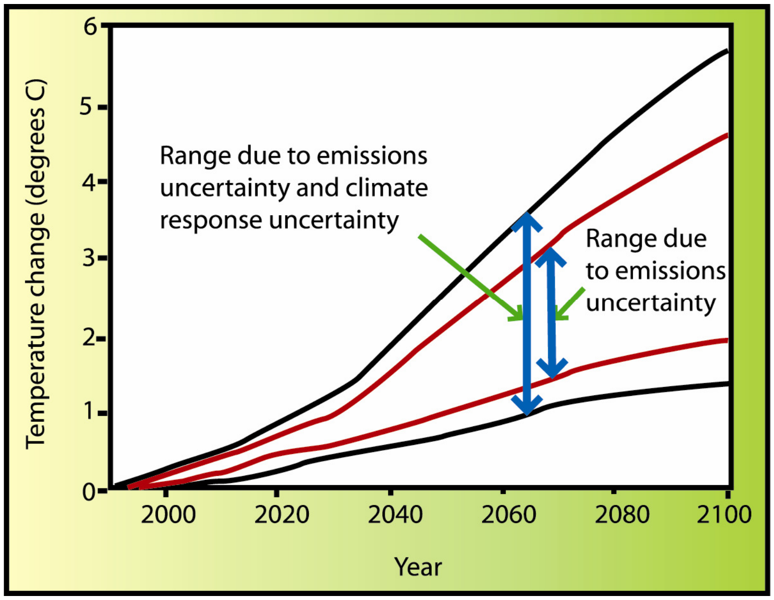


Figure 3.6 Ranges of predicted global warming by 2100 (after IPCC, 1996).

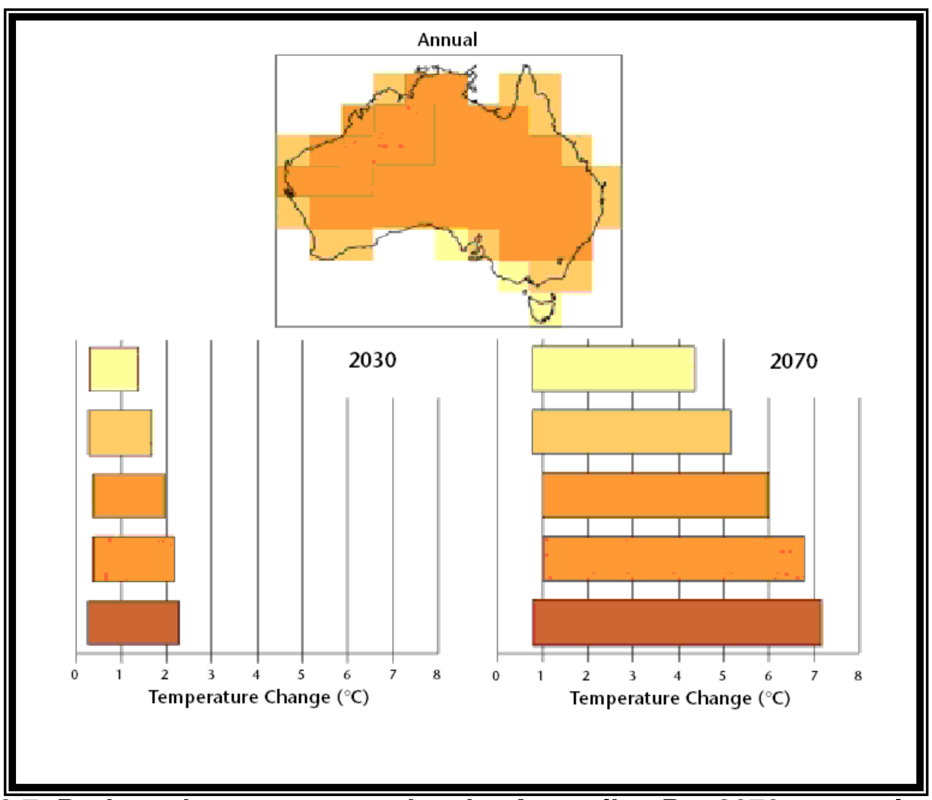


Figure 3.7 Projected temperature rise in Australia. By 2070, annual average temperatures are expected to increase by between 0.8 and 7.1°C (From CSIRO, 2001).

Higher temperatures are likely to lead to increased evaporation rates. The CSIRO (2001) modelled potential evaporation changes, predicting that increases will average between 0 to 8% annually per degree of global warming. The precise implications for the Cape Range are not known as this model implies an increase anywhere between 0-1505mm annually. Considering inferred rainfall fluctuations for the next century are only ±10%, a significant increase in evaporation will lead to a rise in the net moisture balance deficit, leading to further aridity in the region (CSIRO, 2001).

The magnitude of eustatic sea level rise related to climate change is debatable due to the wide range of variables to consider in modelling. However, the IPCC (1996) produced a series of scenarios based upon models of projected CO_2 emissions and related climatic responses (Table 3.2).

Table 3.2 Global sea level rise scenarios - 1996 Estimates (After IPCC, 1996).

Scenario	2030	2050	2100
Low Scenario	0.03 m	0.06 m	0.13 m
Medium Scenario	0.11 m	0.2 m	0.49 m
High Scenario	0.23 m	0.4 m	0.93 m

Although the extent of sea level rise is not currently well understood, this phenomenon must be accounted for in coastal planning for this region.

3.2 Oceanography

Global and local climate changes have a significant impact on prevailing oceanic processes. Temporal and spatial variability of interactions between these processes has contributed to coastal evolution along Cape Range Peninsula (Figure 3.8)

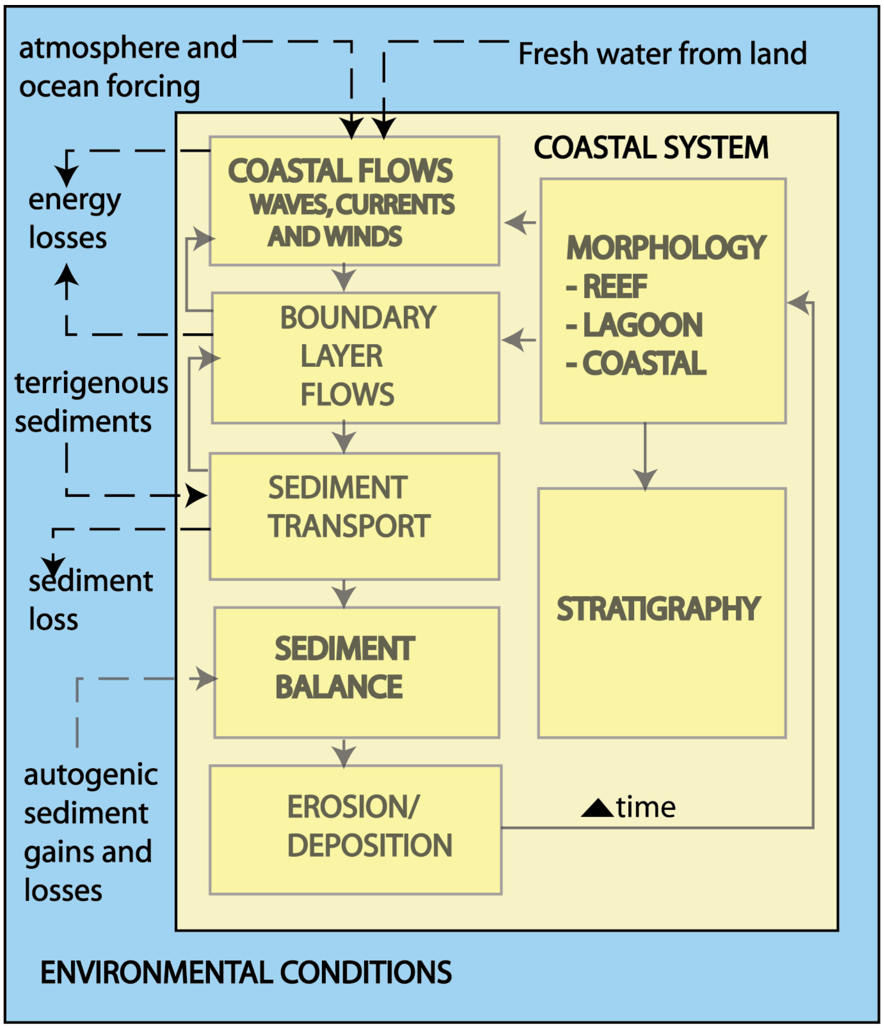


Figure 3.8 Structure and function of the morphodynamic model for the coastal system illustrating interdependence of processes. Dashed arrows represent input-output between the coastal system and the environment. (adapted from Carter and Woodroffe, 1994).

3.2.1 Regional current systems

The regional currents dictating oceanic flow dynamics are complex, with flow directions and current interaction variability controlling coastal processes in an anomalous manner compared to other western continental margins around the world (Pearce, 1991). The West Australian, Leeuwin and Ningaloo Currents represent dominant regional flows.

The West Australian current is a 100-200 km wide cyclonic stream located 100 km offshore, travelling equator ward at a mean velocity of 0.5 m/s (Andrews, 1977). This distal current has a negligible effect on coastal flow dynamics.

Of more significance to the oceanic processes affecting the coast is the Leeuwin Current, a pole ward flow of warm, low salinity water that is responsible for delivering larvae to the region for reef building and maintaining water temperatures for organic survival. Pearce (1991) proposes that this flow is due to the existence of open Indonesian passages magnifying the influence of pressure gradients between warm equatorial waters and the cool southern ocean. This gradient induces an easterly geostrophic flow towards Australia and as it reaches the North West shelf edge it is deflected along this margin. The current maintains a mean width of 50 km and reaches depths of 200 m. Close proximity of the shelf break to the Ningaloo Reef (<10 km) makes the effects of this current significant for reef sustenance (Hearn and Parker. 1988).

McGowran *et al.* (1997) used biological markers to trace temporal variations in the course of the Leeuwin Current since the Tertiary and propose that its existence correlates with interglacial periods, impacting physical processes most during these times.

The Leeuwin Current is strongest between March and August and is essentially absent during the summer months due to the overriding impacts of the wind induced Ningaloo Current (Taylor and Pearce, 1999). This current is driven by strong south-to-south westerly prevailing winds, causing cool water to flow equator ward along the extent of the Cape Range Peninsula. The currents have a dynamic interaction such that the Ningaloo Current dictates the dispersal of coral larvae following the autumnal mass spawning, playing an important role in retaining planktonic biomass within the Ningaloo Reef ecosystem (Taylor and Pearce, 1999).

3.2.2 Lagoonal current systems

The regional flow dynamics of the Ningaloo and Leeuwin Currents are not preserved in the Ningaloo Reef lagoonal systems. Hearn *et al* (1986) attribute this predominantly to bottom friction effects in the relatively shallow lagoonal environment. However, the seasonal variations in current activity are responsible for maintaining water temperatures between 26.6°C in summer and 22.9°C in winter (Hearn *et al*, 1986).

Transport and circulation of the lagoonal waters are principally controlled by reef morphology, waves, tides and winds. Wave pumping across the reef crest is mainly responsible for water inflow to the lagoon. This is caused by constant shoaling of waves against the reef crest and pressure differential production, which drives water into the lagoon at approximately 0.5 m/s (Hearn *et al*, 1986).

Once having crossed the individual reef segments, oceanic water fans and spreads symmetrically through the lagoon along shore parallel channels at 0.1-0.5 m/s (D’Adamo and Simpson, 2001). This flow is exemplified by grooves that represent long-term averages of bottom current trajectories (Sanderson, 1997). Discreet cells of flow evolve as water travels through the lagoon and subsequently exits through passes in the reef to maintain equilibrium on either side of the reef tract (Figure 3.9).

Winds tend to dominate the flow regime closer to the shoreline, generally driving water northwards, with exceptions along morphologically variable coastline. All circulation forces result in a typical residence time for lagoonal waters of less than a day, preventing sustained temperature or salinity stratification (Hearn *et al*., 1986).

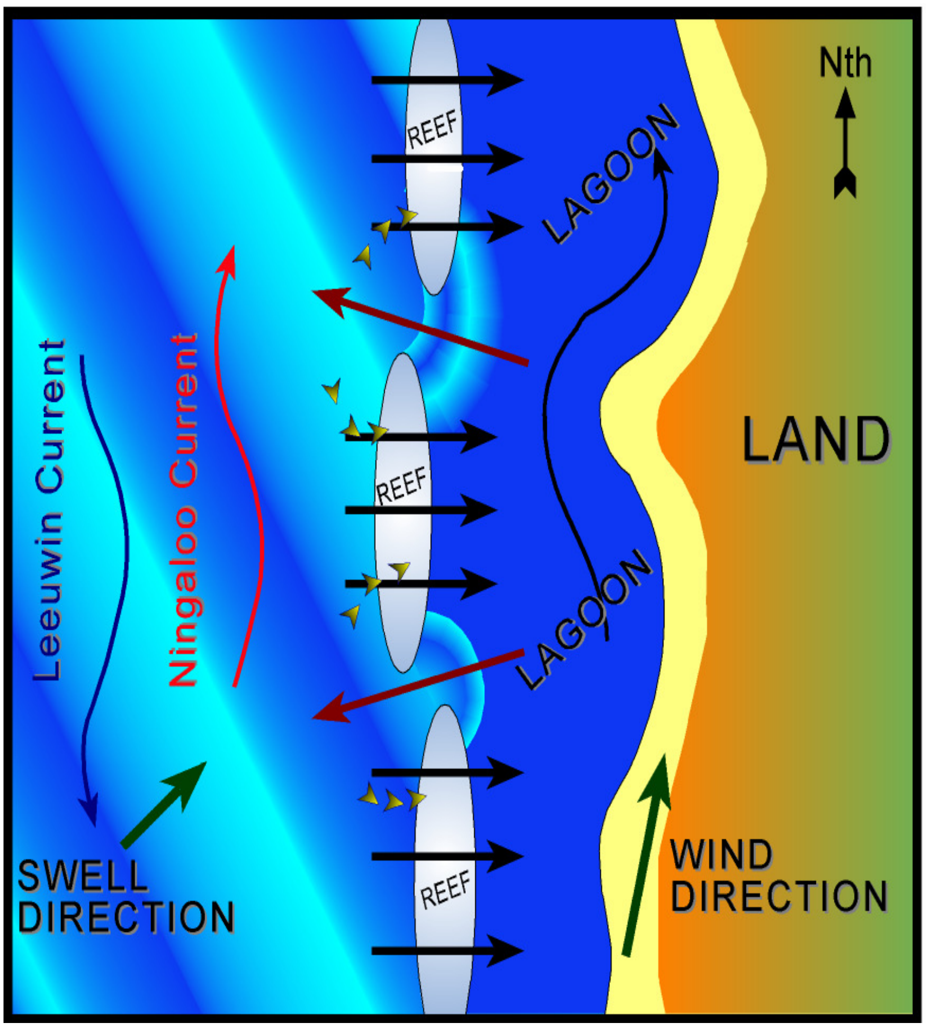


Figure 3.9 Schematic flow regime operating most consistently across Ningaloo Reef, in the lagoon and along the coast. (adapted from Hearn *et al.*, 1986).

3.2.3 Tides and water levels

Tides along the North West Cape are predominantly semi diurnal, with mean spring and neap tidal ranges at Exmouth of 1.8 m and 0.3 m respectively (Sanderson, 1997).

Variations in atmospheric pressure due to the passage of high and low pressure systems have an impact on the magnitude of tidal variation, with changes in barometric pressure altering sea level by about ±10cm/hectopascal (Australian Institute of Marine Science, 2002). This phenomenon superposes astronomical tidal ranges according to the nature and direction of the pressure system and state of the tide, with typical barometric impacts of ±0.3 m (Department of Environment and Heritage, 2002).

Apart from tides, winds change water level on a frequent basis. Typical onshore and offshore winds in the area produce coastal water level changes in the order of ±0.1 m (Department of Environment and Heritage, 2002). Water level variations influence reef exposure, wave magnitude and lagoonal circulation, playing a significant role in sediment transport and coastal morphology.

3.2.4 Waves

The wave climate offshore of Ningaloo Reef shows a strong dependence on weather conditions, characterised predominantly by long period south to south-westerly swell between 12 and 22 seconds with a mean height of 1.5m. Swell waves are generated in the Southern Ocean by low-pressure systems south of 50°S all year round (D'Adamo and Simpson, 2001).

Variations in reef morphology control the spatial distribution of wave attenuation by the action of shoaling, refraction, diffraction and wave breaking over the reef. Sanderson (1997) has calculated that as much as 70%-90% of incident energy is attenuated but spatial variations have not been well defined.

Sea waves generated by prevailing winds superpose the swell component in lagoons. These meteorologically produced waves are characterised by short periods of 1-9 seconds and have an average height 1.2 m. Superposition of sea and swell components forms waves in the lagoon with mean annual height of 2.0 m and maximum up to 4.0 m.

3.2.5 Sediment Transport

Currents generated in the Ningaloo Reef lagoon by tidal forcing, wave action and wind stress are responsible for transport of sedimentary material. Sediments are mainly medium to fine calcareous sands derived primarily from the bio-productivity of the reef system (Sanderson, 2000).

Sediment transport is influenced by ancestral coastal morphology and the temporally variable interaction of processes that control lagoonal circulation.

Near shore sediment transport is predominantly towards the northwest to northeast along the coastline, deposited to form beaches and foredunes. However, sediment accretion and formation of cuspate forelands and salient spits results from more complex circulation patterns defined by morphology of the Ningaloo Reef (Sanderson, 1997). Features of the coastal zone are also influenced by terrestrial sediment transport, with oceanic and terrestrial processes having an interdependent relationship.

3.2.6 Storm and Ebb Surges

Sea surface elevation resulting from TC activity is referred to as storm surge. Surges are typically 1 to 5 m above sea level and 60 to 80 km wide, with magnitude being a function of wind speed, central pressure, shelf slope and tidal stage (Harper *et al*, 2003). Maximum surge heights are not under the eye of a TC where pressure is lowest, but on the left of the eye at the radius of maximum winds (Coch, 1994). In addition to the landward migrating surge component, the subsequent backwash is responsible for causing further erosion and sediment transport, and is termed “ebb-surge”.

Impacts to the coastal zone due to surges are highly variable and inland inundation is a complex function of offshore reef morphology, coastal topography and surge characteristics. Despite the long term implications of surges being poorly understood, their role in morphologic evolution is significant as the water bound energy brought to the coast through these events is capable of transporting sediments to such a degree as to overprint ongoing processes, and become preserved in the stratigraphic record to indicate temporal variations in tropical cyclone activity (Bureau of Meteorology, 1999).

3.2.7 Tsunamis

Earthquakes of magnitude 7 or greater on the Richter scale, associated with the subduction of the Indo-Australian plate beneath the Sunda Arc near Indonesia, are responsible for tsunamis up to every 5 years along the north west coast of Australia (Cummins, 2004) (Collins *et al.*, 1999). Displacement of the water column above the source area causes the onset of a fast moving wave with a wavelength of >100 km and small height differential in deep oceanic waters. As the wave crosses the continental shelf, it runs up to gain amplitude. Due to the continental shelf being only 10 km offshore, attenuation of wave energy is minimal with amplitudes up to 5 or 6 m being retained at the coast (Bryant, 2002)

Impacts of tsunamis are greatest in the lee of reef passes, where wave energy is concentrated. Propagation of the wave trains produced through the lagoon can cause significant coastal erosion and sediment transport anomalous to that of ongoing processes (Figure 3.10).

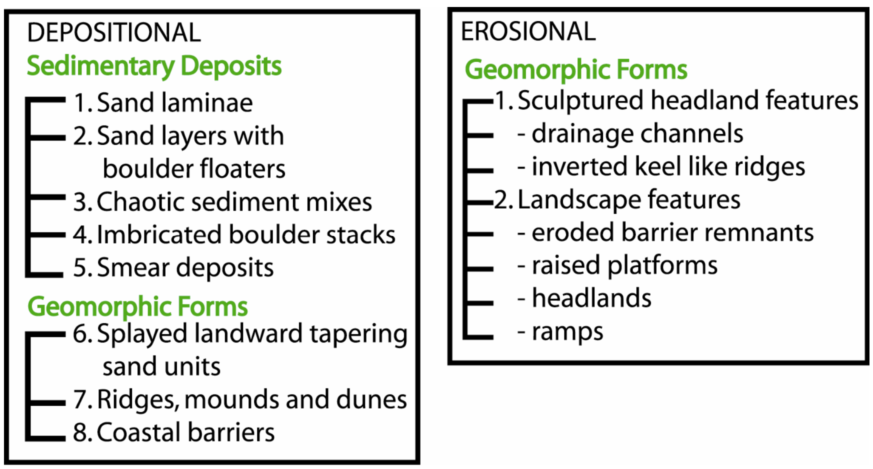


Figure 3.10 The depositional and erosional signatures of tsunami identified for the coast of northern Australia (after Bryant and Nott, 2001).

3.2.8 Seiching

Seiches are long period standing waves typically triggered by storm surges and wind direction and velocity changes, causing a rise and fall of shoreline water levels. The potential effects on coastal evolution are not known in detail. However, DAL Science and Engineering (2002) suggest they play an important role in coastal development as Ningaloo Reef effectively acts as a barrier prohibiting energy transformations spreading out to sea, causing a rebound of energy, resulting in a back and forth "rocking" action of water levels in the lagoon that influences sediment transport.

4 QUATERNARY EVOLUTION

Episodic uplift coupled with eustatic variations prior to the onset of the Last Interglacial, 128 ka BP, is responsible for the development of the terraced Cape Range Anticline, which defines the eastern and northern boundary of the coastal plain in the study region.

Geologic and geomorphologic expression of the coastal plain has evolved in response to eustatic variations since 128 ka BP, with adjacent range lithology and morphology dictating the spatial development of drainage systems, defining alluvium dispersal. 6 major stages of Quaternary evolution are evident and outlined in Table 4.1.

Table 4.1 Major stages of Quaternary Coastal Plain evolution and geologic and geomorphologic responses (Adapted from Hocking, 1990; Wyrwoll *et al.*, 1992).

Stages of evolution	Sedimentary Record	Geomorphology
Stage 1 128-121 Ka BP (Interglacial High stand, sea level 4 m)	- Bundera Calcarenite: Tantabiddi Member - Bundera Calcarenite: Mowbowra Conglomerate Member	Low gradient coastal plain foundation up to 5 km inland from current shoreline.
Stage 1b ? Timing (highstand sea level +2-3 m)	- Bundera Calcarenite –Aeolian Member, Mowbowra Conglomerate Member	2-7 m ridge, discontinuously exposed along coastal plain between 800 m and 4.9 km from current shoreline
Stage 2 118 Ka 30 Ka (Regression)	- Bundera Conglomerate: Mowbowra Conglomerate Member - Red alluvium cover upon Tantabiddi Member of Bundera Calcarenite	-Widespread, low relief coastal plain surficial alluvium cover - Ephemeral Channels and alluvial fans
Stage 3 30 ka – 18 ka Lowstand, sea level –125 m)	- Siliceous and calcareous Longitudinal dunes - Alluvially derived calcareous conglomerate, calcirudite and mudstone	- Longitudinal dunes up to 15 m high and sand plains with low relief - No exposure of conglomerate - Ephemeral Channel and alluvial fans
Stage 4 18 Ka – 5.3 Ka (Transgression)	- Gypsiferous sand silt and clay flats - Alluvially derived conglomerate, calcirudite and mudstone	- Low relief supratidal saline Flats - Intertidal flats and mangrove swamps - Alluvial fans - Ephemeral channels
Stage 5 5.3 Ka – Recent (highstand, sea level +1-2 m – modern sea level)	- Unlithified to poorly lithified calcarenite and grainstone dunes and blowouts - Unlithified to poorly lithified conglomerate, calcirudite and mudstone	- Prograded Mobile and vegetated beach ridges - Blowouts - Modern Foredunes - Active Beaches - Modern channels and alluvial fans

4.1 Stage 1a

The foundation of the modern coastal plain formed during the most prominent interglacial period of the Quaternary, peaking between 128 and 121 Ka BP (Stirling *et al*., 1998). This period was characterised by +3 to 4 m sea level, extending inland to the Tantabiddi scarp, which defines the modern boundary of the coastal plain. The package of sediments deposited in this phase is defined as the Tantabiddi Member of the Bundera Calcarenite (Hocking *et al*., 1990).

Colonisation of the Tertiary Tulki Limestone, morphologically defined by the ancestral physiography of this unit, led to the development of coral and coralgal reefs at depths between 0.5 and 1 m below sea level and an associated lagoonal environment analogous to that of the modern Ningaloo Reef (McCulloch and Esat, 2000). Two distinct facies are recognised in this member, with coral and coralgal reef deposits extensively preserved as framestone and lagoonal deposits represented as skeletal grainstone and packstone to rudstone. These deposits crop out adjacent to one another but more frequently with the lagoonal deposits overlying the framestone, representing progradation of the lagoonal facies as sea level fell and earlier reef tract deposits became inundated (Figure 4.1a).

Along modern and relict ephemeral channels, the coralgal reef and lagoonal deposits are laterally replaced by the Mowbowra Conglomerate Member of Bundera Calcarenite, a limestone pebble to cobble calcirudite consisting of recognisable detritus from Tertiary limestones of the adjacent Cape Range (Figure 4.1b) (Wyrwoll *et al*, 1992)

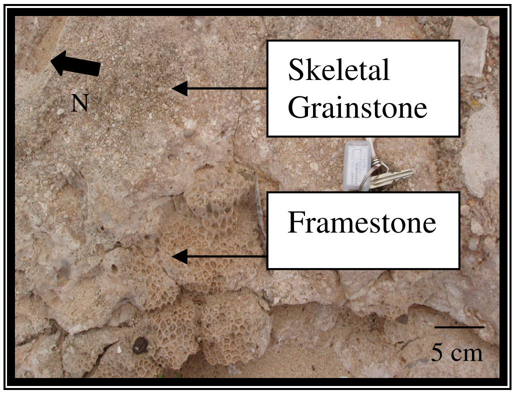
4.2 Stage 1b

Following the major Last Interglacial, an overall regressive phase was at some time subject to a climatically derived pause. This is evident through the widespread occurrence in areas E, F and G of a discontinuously preserved calcareous ridge, the Tantabiddi Aeolian Member of the Bundera Calcarenite, representing shoreline and foredune environments up to 300 m seaward of the inland extent of stage 1a deposits.

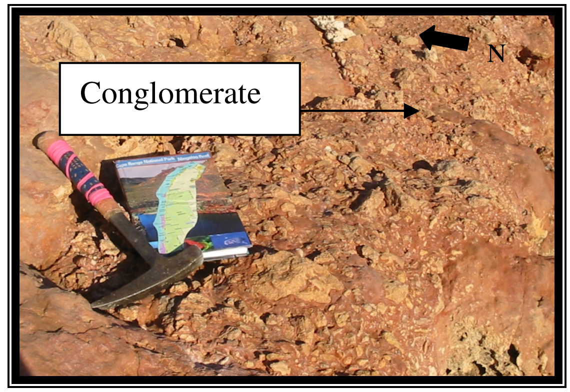
Sporadic outcrops of bevilled stage 1a deposits seaward of the ridge provide evidence of littoral zone reworking of earlier reef deposits during this period, temporally distinguishing this phase from stage 1a.

The lower margin of the ridge is primarily grainstone, interpreted as a beach deposit, and the upper margin is made up of a moderate to well sorted aeolian derived calcarenite, most likely representing relict foredunes (Figure 4.1c and 4.1d). The spatial relationship of these two deposits suggests sea level maxima is represented by the beach deposits and overlying foredunes developed as a response to sea level regression.

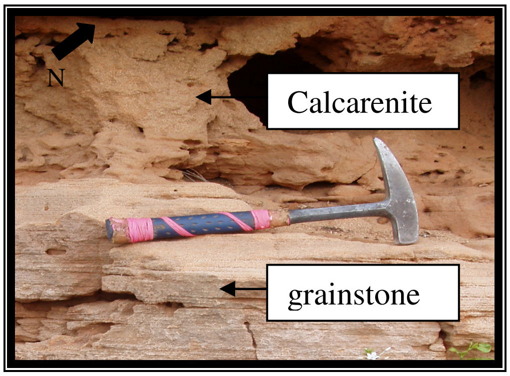
Thermoluminescent dating is currently being conducted to aid in gaining a better understanding of the timing of deposition and the likely mechanisms for development. Kendrick *et al*. (1991) suggest this unit was deposited in a second peak of the preceding interglacial, in which sea level fell and later stabilised due to a second peak of warming (Figure 4.2). This hypothesis is considered the most likely scenario. However, until further research is carried out and dating complete, another scenario of sea level fall and a subsequent rise at some time later in the Pleistocene cannot be discounted (Figure 4.3).



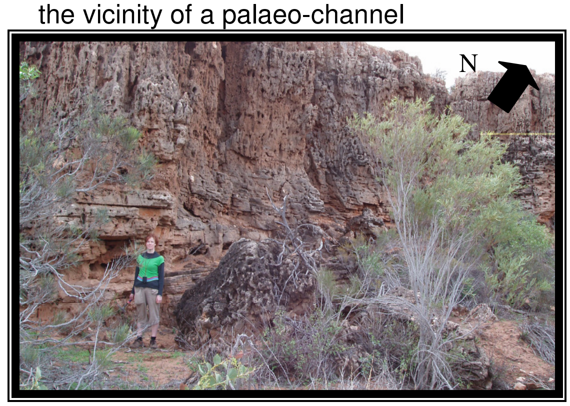
a. Last Interglacial Reef, coral framestone overlain by lagoonal grainstone.



b. Mowbowra Conglomerate outcrop in the vicinity of a palaeo-channel



c. Boundary between lower beach grainstone and aeolian calcarenite.



d. Ridge morphology at Pilgonaman Gorge

Figure 4.1 Stage 1a and 1b units in Area F, Cape Range National Park

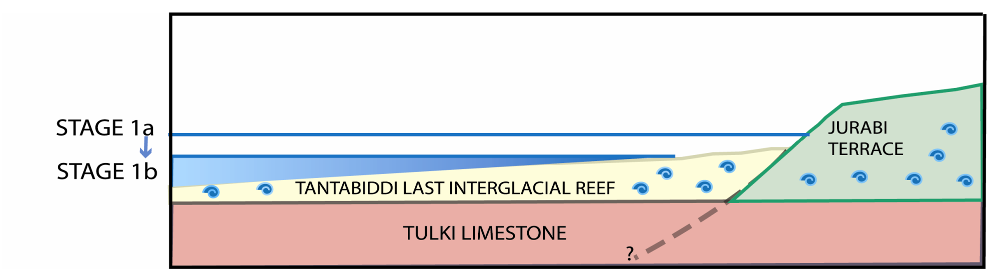


Figure 4.2 Model of likely mechanism for ridge formation in stage 1b, a direct sea level regression and subsequent pause.

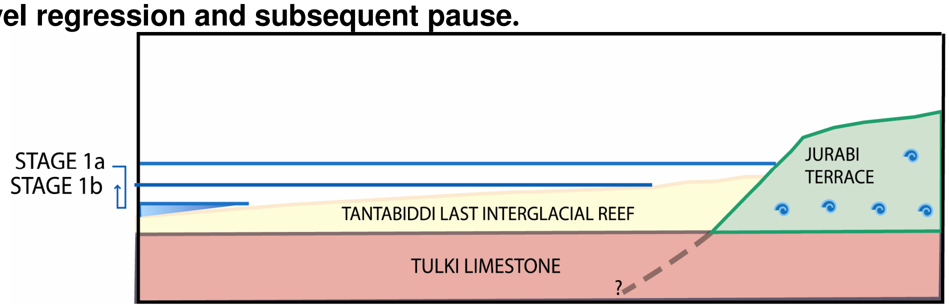


Figure 4.3 Model representing possible sea level regression and subsequent transgression followed by a pause and stage 1b ridge development.

4.3 Stage 2

An overall regressive phase subsequent to stage 1b, lasting until a glacial onset at 30 ka BP was characterised by continued development of alluvial systems in the modern terrestrial realm to 125 m below the modern shoreline, marking the extent of the lowest sea level attained (Peltier, 2002). During this period, drainage from the adjacent Cape Range in Areas E, F and G played a major role in coastal plain evolution. Incision of the ridge formed during stage1b along channels has dictated its modern spatial preservation. Furthermore, climatic aridity of this period led to extensive calcretisation of this ridge.

Alluvial fan development in the vicinity of the terminus of ephemeral channels, coupled with occasional flooding is responsible for the deposition of an almost continuous layer of fine to medium grained red alluvium, upon stage 1a deposits.

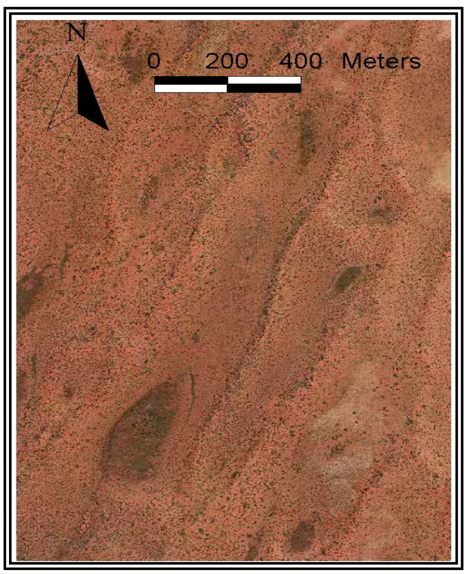
The spatial distribution of alluvial related erosion and sedimentation in this period has played a significant role in the evolution of the modern Ningaloo Reef as the morphology and constituents of substrate developed at this time influenced later coral colonisation. In areas where large channels developed, a subsequent lack of suitable substrate for recolonisation has led to an absence in reef growth.

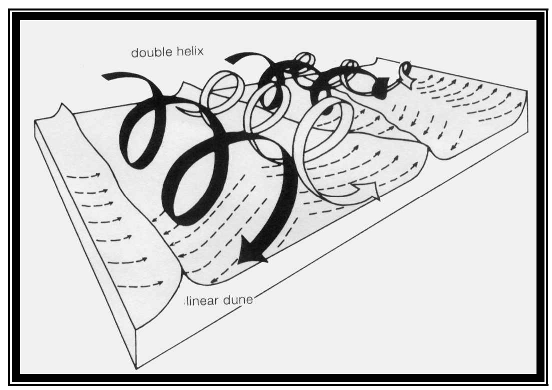
4.4 Stage 3

A glacial maximum extended from 18 to 30 Ka BP, with an accompanying sea level of -125 m (Van de Kaars and Dekker, 2003).

Similar alluvial processes continued into this period from preceding times, with geologic and geomorphologic responses correlative with those of stage 2.

This phase has had a further distinct impact on the regional coastal and inland setting, with the development of longitudinal dune fields in the northern and southern regions of Cape Range Peninsula, exposed to the east of the Cape Range in Area E and to the north and east of the Range in Areas G and H. These dunes have an approximate north-to-north east trend, suggesting prevailing winds parallel to this at the time of formation (Figure 4.4a). Mechanisms for development are complex, and current theories propose vortices transporting sediment in swales and subsequent deposition as ridges (Livingstone and Warren, 1996) (Figure 4.4b).





a. North to northeast trending Longitudinal dunes in area G

b. Pairs of thermally induced roll-vortices sweep sand from inter-dunal swales (from Livingston and Warren, 1996)

Figure 4.4 Typical dunes at the north of Cape Range and the proposed mechanism of roll-vortices influencing their development.

4.5 Stage 4

Following the Last Glacial Maximum, sea level rose until 5.3 ka BP, reaching a maximum of +1 to 2 m at this time, with a portion of this level attributed to continental isostatic loading and minor coastal subsidence resulting from glacial ice melting (Collins *et al*., 1993; Baker *et al*., 2001; Yokoyama *et al*., 2001).

The earliest stage of this period was characterised by shelf erosion and shore face retreat which resulted in Late Pleistocene and early Holocene sediments being stripped off the shelf surface, remobilised and transported landward as the sediment source for terrestrial dune development. Persistence of alluvial activity restricted stripping of sediments in the vicinity of major channels, as sediment supply remained high in these regions. Subsequently, Last Interglacial Reef deposits were not exposed to provide a suitable substrate for coral recolinisation as Ningaloo Reef began development.

7.57 ka BP marks the initial growth of the modern offshore Ningaloo Reef. This reef has since grown to a maximum thickness of 18 m and continues to develop to date. Robust coral framestone, often bound by encrusting coralline algae has colonised the underlying reef initially developed in the Last Interglacial period (stage 1a) (Collins, 2002). The reef has not developed in areas of relict channels and hence a series of passes are a distinct morphologic feature that play a role in lagoonal circulation and related coastal processes defining shoreline morphologic and lithologic development.

As sea level transgressed, intertidal bays developed in local depressions as coastal barriers were breached and upon reaching a highstand, these areas became permanently inundated to form shallow marine embayments. The majority of area H was drowned at this time and relicts of marine inlets, outlets and embayment fill define the primary geological and geomorphologic expression of this area. Also, a large portion of the central region of area E was inundated during this period.

During this highstand, the marine embayments at Mangrove Bay in Area F and in small patches in the east of Area H were populated by mangroves. Only remnants of these mangrove swamps are exposed in Area H, whereas 1.7 Km^2 is still preserved at Mangrove Bay (Kendrick and Morse, 1990) (Figure 4.5).

Figure 4.5 Mangrove intertidal flats and distal beach ridges towards the modern shoreline at Mangrove Bay.

The Holocene highstand palaeo-shoreline is represented in the modern environment as the most landward dune unit in a series of relict foredunes that have since developed.

4.6 Stage 5

Sea level has fallen since the closing stages of the mid Holocene highstand. During this 5.3 ka period, the majority of marine embayments have been drained and are now expressed as supratidal saline flats and intertidal mangrove swamps (Kendrick and Morse, 1990).

Morphology and spatial distribution of ephemeral channels and associated alluvial fans has remained similar to preceding times as evidenced by spatially correlative relict offshore alluvial fans. However, as sea level has declined, progradation has occurred where alluvial sediment supply and erosional processes have been significant enough to prevent barring from modern dune development.

As sea level regressed, foredunes prograded in response, resulting in the development of a series of beach ridges, typically extending to the modern foredune. Ridge orientation is defined by palaeo-shoreline morphology, and is typically approximately parallel to the modern coastline. Morphology is a complex function of spatial differences in sediment transport rates, vegetation cover, and erosional processes (Hesp, 2002).

Spatial variations in the seaward accretion and subsequent width of ridge sequences since 5.3 ka BP are dependant on ancestral reef morphology (stage 1a), offshore reef characteristics and longshore currents. In areas where the Tantabiddi Member extends further seaward, ridges have tended to prograde to the greatest extent, forming sedimentation nodes. As longshore currents typically flow to the north, coastlines with a southerly aspect act as a sediment trap and hence commonly extend further seaward than northerly facing areas.

Cuspate forelands and smaller salient spits have developed in many areas adjacent to passes in the Ningaloo Reef as wave refraction and associated anomalies from the usual northerly sediment transport regime have led to sediment accretion in these areas. (Sanderson, 2000) (Figure 4.6).

Where vegetation is sparse and strong oblique onshore winds have mobilised dune sediments in locations with a low sediment supply, blowouts have developed. These features are expressed as saucer, trough and cup shaped depressions between dunes (Hesp, 2002). In contrast, large mobile dunes have formed in poorly vegetated areas with abundant sediment supply. These regions have primarily developed where shorelines have a southerly aspect, trapping northerly longshore sediment drift.

Calcareous modern foredunes and active beaches are the most prominent features of the nearshore zone and are evolving to date. The Tantabiddi Member is exposed along the shoreline in areas with insufficient sediment supply to enable burial. Lagoonal currents are primarily responsible for morphologic definition of the coastline, and channels reaching the coastline sporadically breach the dunes, depositing pebbles and cobbles in this zone.

a. Turquoise Bay Cuspate foreland (N:7553400, E:797800)

b. T-Bone Bay salient spit (N:7561400, E:801300)

c. Sandy Bay salient spit (N:7538700, E:792800)

Figure 4.6 Cuspate foreland and salient spits formed through wave refraction at reef passes and anomalous sediment transport.

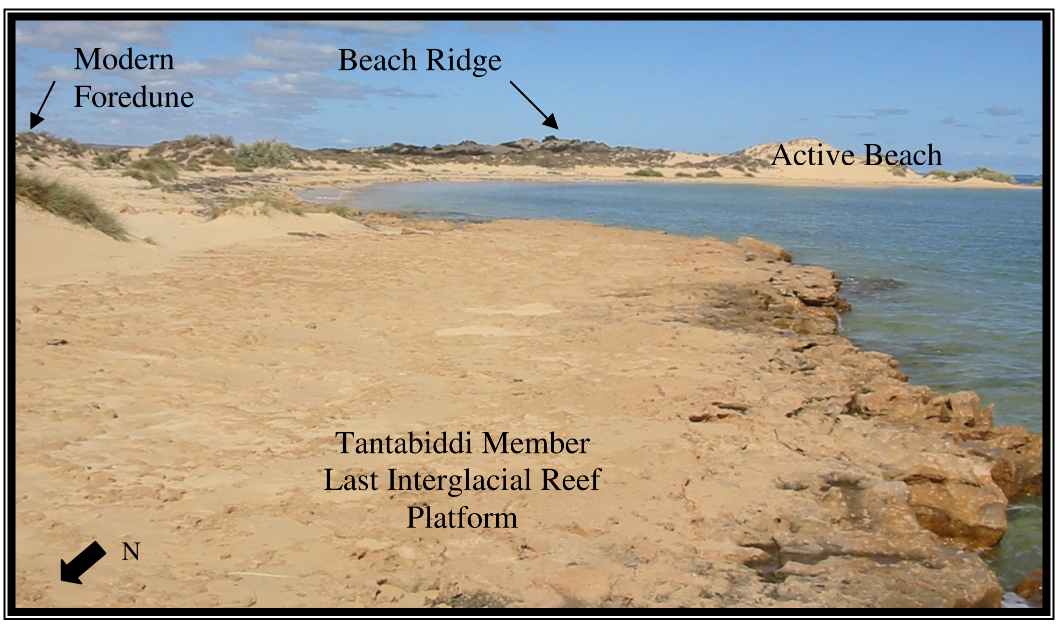


Figure 4.7 Typical morphologic features of the coastal zone. Last Interglacial Reef, beach ridges, active beaches and modern foredunes. 350 m to horizon.

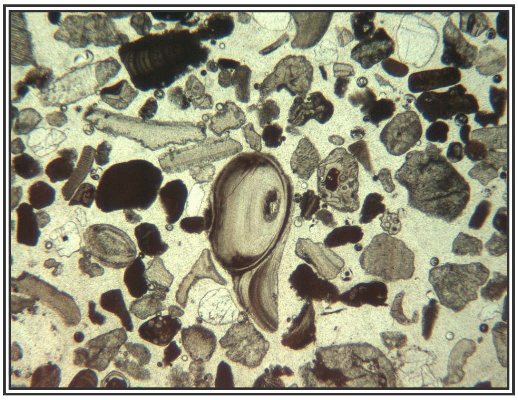
5 GEOLOGY AND MORPHOLOGY OF STUDY AREAS E-H

Geologic and geomorphologic expression is spatially variable along Cape Range Peninsula. To achieve the greatest possible detail in delineation of variations, the dominant features of each area have been characterised.

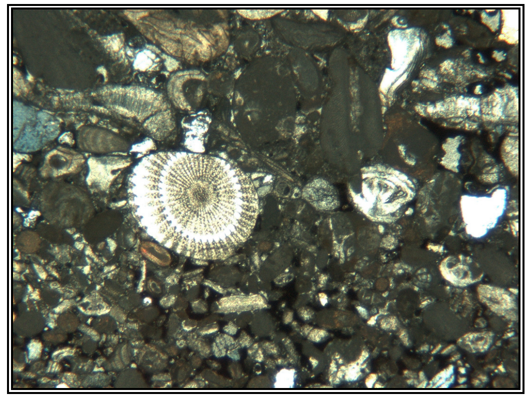
Areas E, F and G are situated adjacent to Cape Range Anticline and are subject to influences of drainage from this structure, and hence the inland portion of the coastal plain is commonly characterised by similar alluvium deposits.

Area H is located to the northeast of the anticline and alluvial processes have not played a major role in evolution of the modern coastal plain. The characteristic geology of this area is distinct from the three other study regions.

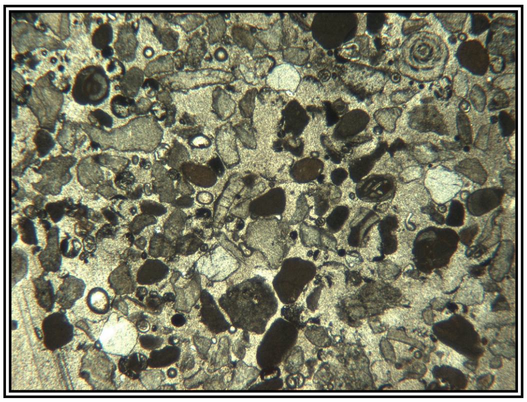
Lithologic descriptions of the major geological units in the region are defined in Appendix 6 and examples of typical characteristics are illustrated in Figure 5.1.



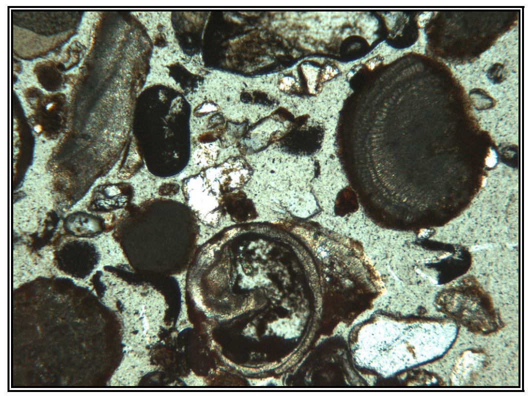
Sample 25/7B1CH, Beach Sand. Open Marine assemblage, mollusc in centre (field of view = 6.5 mm, PPL)



Sample 27/7GCH. Bundera Limestone, lagoonal deposit. Mixed skeletal grains (field of view = 6.5 mm, XPL)

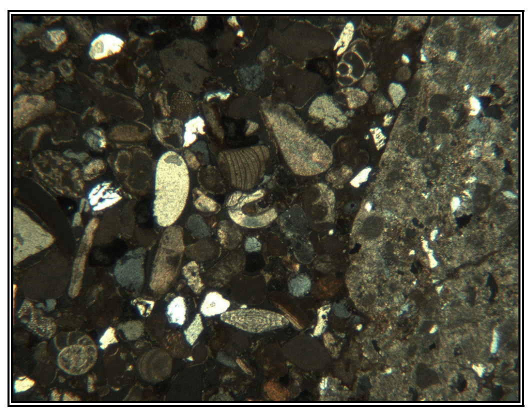


Sample 25/7E2CH. Modern dune sand. Fragmented open marine assemblage (field of view = 6.5 mm, PPL)



Sample 24/7ECH. Longitudinal Dune Sand Micrite rims around skeletal and quartz grains (field of view = 6.5 mm, XPL)

Sample 24/7JCH. Bundera Calcarenite Aeolian Member. Micritised skeletal Fragments, coralline algae central. (field of view = 1.5 mm, XPL)



Sample 28/4ICH. Mowbowra Conglomerate. Micritic clast adjacent to Quartz and calcareous lithoclasts (field of view = 6.5 mm, XPL)

Figure 5.1 Thin section images of samples from major units characterising coastal plain lithology. (PPL= Plain Polarised Light; XPL = Cross Polarised Light).

5.1 Bundera Coastal Protection Area (Area E)

The coastal plain of Bundera Coastal Protection area extends for 13.5 km from north to south and ranges between 300 and 2600 m in width, bordered on the eastern margin by Cape Range Anticline.

The Jurabi Terrace Member of the Bundera Calcarenite forms the eastern border of the coastal plain. This unit formed in an environment analogous to the Last Interglacial and the modern Ningaloo Reef, and is characterised by a similar lithology but evidence of recrystallisation.

Landward of this unit, Exmouth Sandstone and Tulki Limestone are the most dominant geological units to crop out, extending to the eastern margin of the anticline. Landward of these units, extensive fields of Late Pleistocene longitudinal dunes, trending north to northeast, are representative of the last glacial maximum arid environment. These dunes are typically carbonate rich with a well developed profile of brown sand overlying pale sand with carbonate segregations and well developed calcrete horizons (Wyrwoll *et al*., 1992).

The geology of the inland portion of the coastal plain is dominated by the Tantabiddi Terrace Member of the Bundera Calcarenite (Last Interglacial Reef) overlain by alluvium. In the vicinity of ephemeral channels, alluvium is up to 2 m thick, thinning laterally and seaward.

The Tantabiddi Aeolian Member of the Bundera Calcarenite sporadically crops out along the inland area of the coastal plain. This unit is typically deeply calcretised and at varying distances from the coastline dependant upon palaeo-coastal morphology.

A large supratidal saline flat characterises the central region of the area. This unit is representative of the mid-Holocene highstand, whereby a sea level of +1 to 2 m led to coastal dunes being breached and marine inundation in topographically low areas (Figure 5.2). Subsequent regression has led to drainage of this flat and the formation of a series of prograded linear beach ridges. These ridges extend between 15 and 460 m from the modern coastline.

Modern foredunes lie parallel to the shoreline, landward of active beaches often characterised by outcrops of Last Interglacial Reef in areas where sediment supply is not great enough to inundate this unit.

Geological units in Area E are comprehensively defined on the accompanying CD ROM and Figure 5.3 is representative of the typical coastal plain and adjacent hinterland of Cape Range Anticline in the central portion of the area.

Figure 5.2 Supratidal saline flat and Cape Range Anticline in the background.

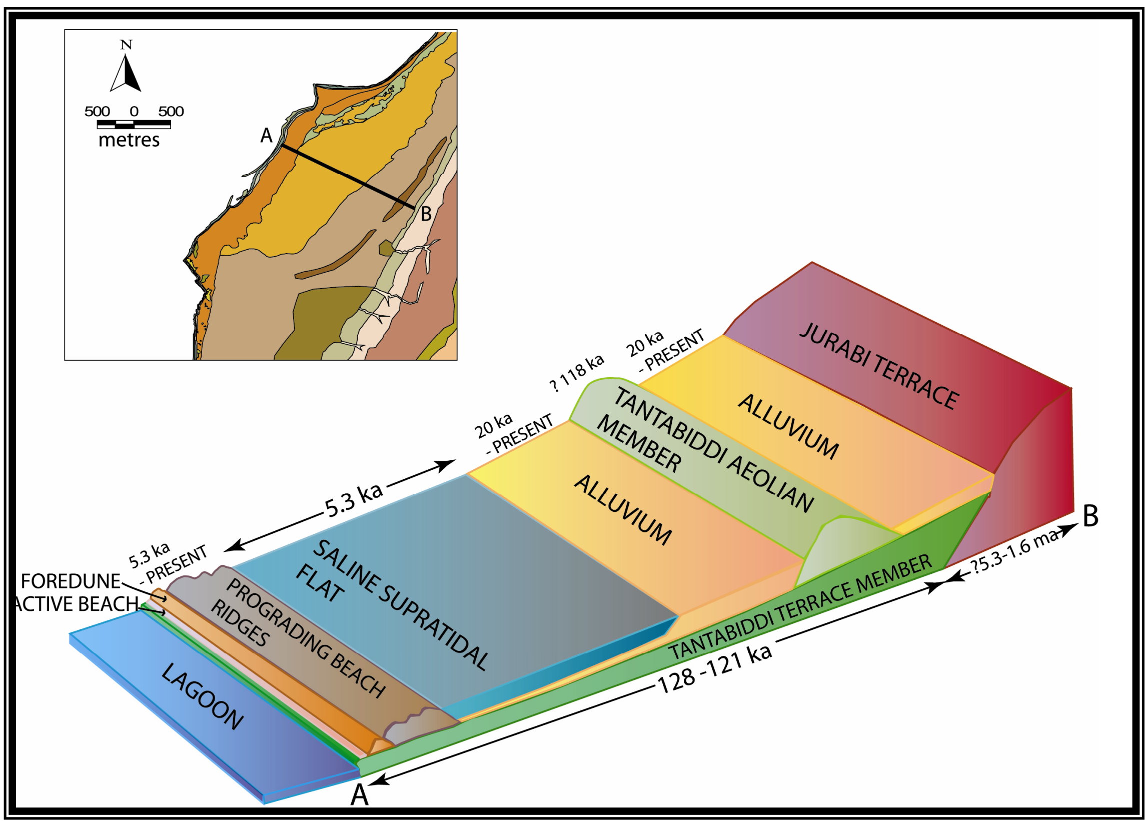


Figure 5.3 Coastal Plain geology and morphology in the central portion of area E.

5.2 Cape Range National Park (Area F)

Area F extends 50 km from north to south and is characterised by a coastal plain ranging between 700 to 2600 m in width. The national park boundary extends beyond the study region, up to 10 km inland, and only the coastal plain and adjacent anticlinal hinterland have been analysed.

Coastal plain geology is similar for the majority of the region with the exception of a large mangal area in the north at Mangrove Bay (Northing: 7568000; Easting: 804000). Spatial variations in the morphology of individual units are the primary variable controlling landscape differences.

Cape Range Anticline Terraces, defining the eastern boundary of the coastal plain, are characterised by a higher relief in this area than the three other study areas, with a maximum height of 314 m at Mount Hollister (Hocking, 1990).

The Jurabi Member of the Bundera Calcarenite defines the boundary of the coastal plain and the lowest uplifted terrace member of the Cape Range Anticline. The lithology of this unit is analogous to that in Area E. A notched second bevilled terrace in the lower margins is evident in a number of locations, most extensively preserved near Mandu Gorge (N:7547900, E:797600) and Yardie Creek (N:7528600;.E:789800). This possibly formed in the littoral environment at the peak of the Last Interglacial, 128-121 ka BP.

The inland area of the coastal plain is primarily composed of alluvium overlying the Tantabiddi Member and temporally corresponding alluvially derived Mowbowra Conglomerate. Ephemeral channels and associated linear, irregularly formed alluvial fans are responsible for deposition of this calcareous, pebbly alluvium. This unit ranges in thickness from 2 m in the vicinity of major channels and is absent in a small area at the northern boundary of the region (N:7570800; E:806550).

Periodic outcrops of the Tantabiddi Aeolian Member of the Bundera Calcarenite snake along the extent of the inland region of the coastal plain. This unit has been eroded in the vicinity of channels and exhibits extensive calcretisation as in Area E.

Remnant mangrove swamps at Mangrove Bay represent relicts of the mid-Holocene highstand, 5.3 ka BP. The geology of this area is spatially variable, with portions bordered at the seaward margin by recent dune and beach facies and other regions extending to the shoreline. Sediments are primarily calcareous and quartzose mudstones derived from the marine environment and run-off from the adjacent Cape Range.

Seaward of alluvial plains and mangrove swamps, the coastline is defined by relict foredunes that have prograded seaward as sea level has fallen over the past 5.3 ka, to form a series of beach ridges. These ridges are typically characterised by unlithified grainstone and vary in morphology, individually ranging up to 6 m in height and forming dune fields up to 450 m inland.

Cuspate forelands, salient spits and ancestral Tantabiddi Member headlands are the most common areas in which ridge sequences are relatively wide, as these areas have been subjected to the greatest magnitude of sediment accretion. A large cuspate foreland has developed at Turquoise Bay and smaller salient spits at Osprey Bay, Sandy Bay and Lakeside due to higher rates of sediment erosion in the southerly margin of the features and deposition to the north.

At the coastal margin, modern foredunes up to 6 m in height are bordered by active beaches with sporadic outcrops of Last Interglacial reef grainstone and framestone along the coast in areas where sediment supply is not great enough to have caused burial of this unit.

The geology of this area has been defined in a series of 8 maps with a scale of 1:15000, and represented as maps 1and 2, from north to south respectively. Furthermore, a digital version of the geology of the area is on the accompanying CD ROM.

Figure 5.4 is a representative cross section of the coastal plain at Turquoise bay, defining the typical morphology and geological units of Area F.

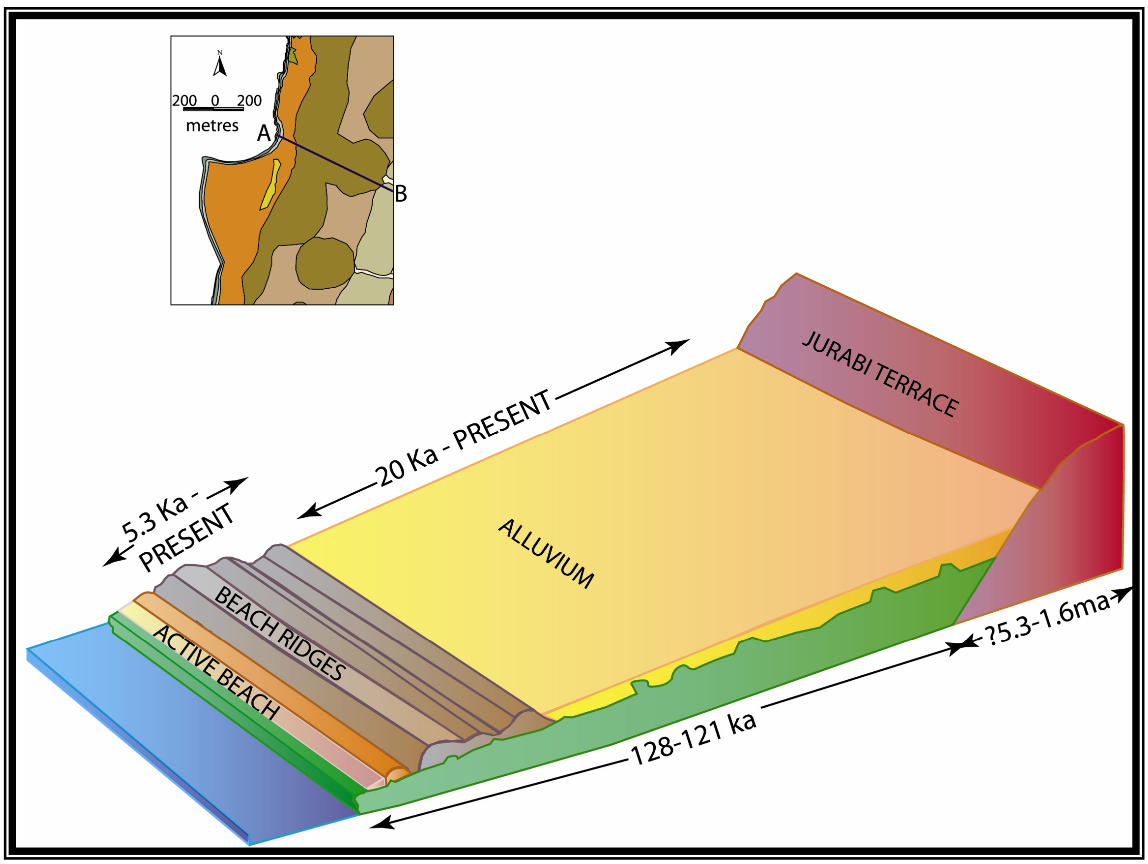


Figure 5.4 Coastal Plain geology and morphology at Turquoise Bay, Area F.

5.3 Jurabi Coastal Park (Area G)

The inland portion of the coastal plain, foredunes and beaches in area G are geologically and morphologically analogous to that of area F. However, prograded dune systems differ significantly and the northeastern area is characterised by longitudinal dunes. A comprehensive account of geology can be viewed on the accompanying CD ROM.

The northeastern margin of the area is characterised by 25 km^2 of longitudinal dunes consisting of red calcareous and siliceous sands, with little pedological development. Two thermoluminescence ages of 23.4±6.7 and 16±1.7 ka BP confirm depositional correlative with the last glacial maximum (Wyrwoll *et al*., 1992).

Extensive dune fields have developed in areas where the Tantabiddi Member inherently extends most seaward, hence providing a substrate for beach ridge progradation. Initial ridge morphology is commonly absent as sediments have remobilised and formed a series of mobile dunes and blowouts. Areas with low sediment supply are typically characterised by inter-dunal depressions. Holocene calcareous sands have been variably eroded and are occasionally absent.

The most extensive dune field is in the Jurabi Coastal Reserve (N: 7578000; E: 809943) (Figure 5.5). A schematic view of the typical geomorphologic and geologic features is illustrated in Figure 5.6.

Figure 5.5 Inter-dunal depression in Jurabi Coastal Reserve, Holocene sediments have been eroded leading to exposure of the Tantabiddi Member.

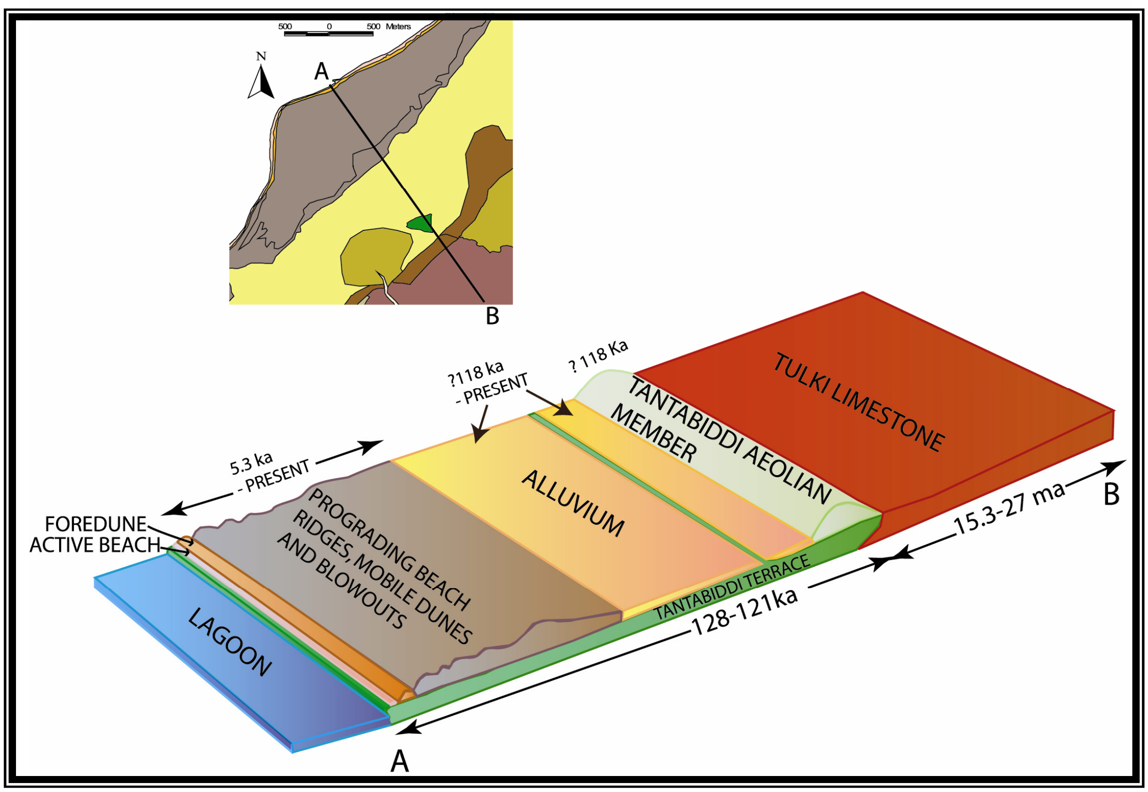


Figure 5.6 Coastal landscape in Area G, illustrating extensive Holocene dune fields.

5.4 Northern Cape (Area H)

Area H is located to the east of Cape Range Anticline and is not morphologically or lithologically influenced by this structure to the same degree as the other study areas.

This area is characterised by longitudinal dunes, low relief supratidal saline flats and fringing coastal dune sequences. The Tantabiddi Member forms the foundation of these units and its ancestral morphology plays an important role in defining the profile of the modern coastline.

The western margin of the area is characterised by the fringe of the longitudinal dune field that dominates the inland region of Area G. Outcrops of dune remnants within late Holocene coastal dunes suggests that they were a characteristic feature of this area prior to this time and were eroded in low lying areas through marine inundation.

Topographic lows at the north west of the Cape and 6.8 km to the south east of this point have been identified respectively as the entrance and exit channels of marine embayment formation at this time. Drainage of this area has subsequently led to the development of supratidal saline flats (Figure 5.7).

Coastal fringing dune sequences vary in width from 50 m to 1700 m with larger dune fields typically characterising the eastern coastline of the area.

The typical geologic and geomorphologic expression of this area is illustrated in Figure 5.8, and the specific geology can be viewed in more detail on the accompanying CD ROM.

Figure 5.7. Tantabiddi Member outcrop on the outer margin of a supratidal saline flat, with Holocene dunes towards the coast.

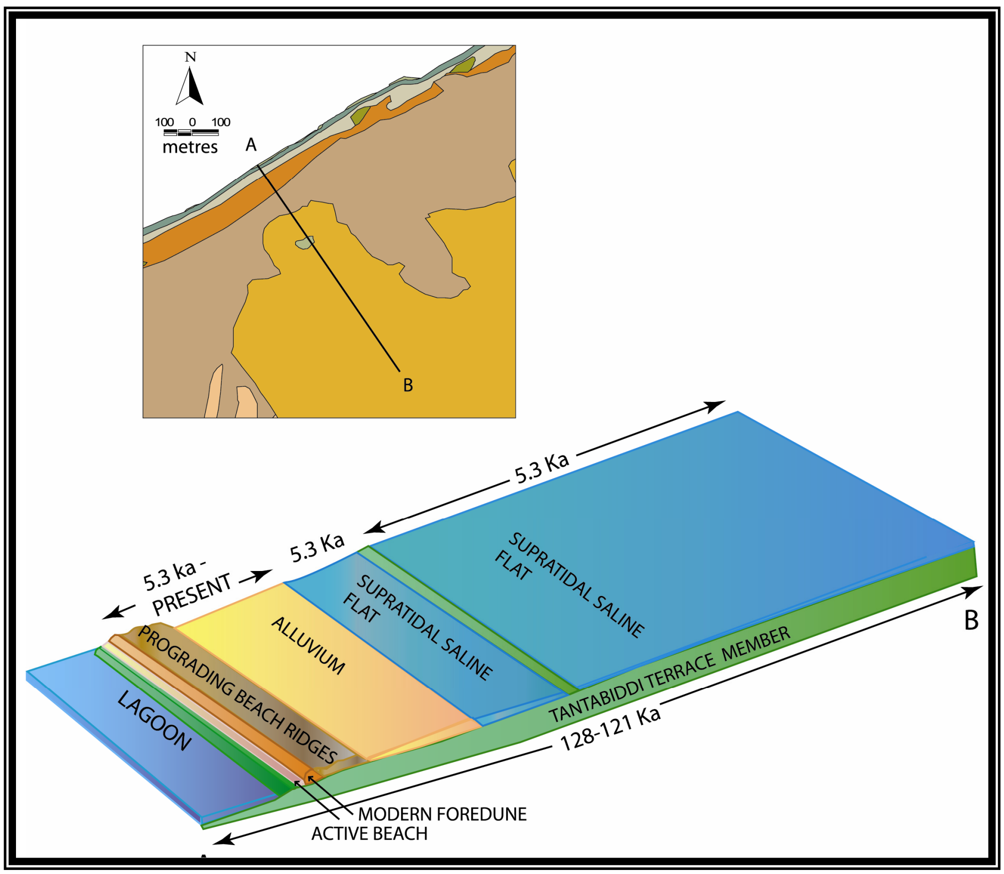


Figure 5.8 Spatial layout of the typical geology and morphology of area H.

6 LAND UNITS

6.1 Land Unit Definition

Delineation of geological units beyond lithologic and morphologic descriptions enables land managers to gain a more conclusive understanding of overall land characteristics. For this reason, the term “land unit” has been developed to further define substrate capacity and land use patterns, as defined in 1.3.3.

Land unit description enables natural resource managers to observe characteristics of specific areas using a multidisciplinary approach in definition of sustainable areas for land use.

6.2 Substrate Capacity In Land Unit Classification

Substrate capacity is defined by a unit’s consolidation, thickness, vegetation cover, slope and runoff potential, as outlined in 1.3.3. Predominant features of each unit have been determined through qualitative field assessment and an overall substrate capacity index is defined based upon an overall combination of each variable. Comprehensive maps of substrate capacity can be viewed on the accompanying CD ROM, as “subcap” on the “geology” shapefile.

6.3 Land Units In the Study Region

Classification of land units is based upon lithologic characterisation of major geological units, documentation of spatial variations in substrate capacity and land use as defined in 1.3.3. Table 6.1 outlines the units delineated in the study region.

Table 6.1 Geological features, substrate capacity and land use features of the 18 land units present in the four mapped areas of the study region

UNIT	DESCRIPTION	SUBSTRATE CAPACITY INDEX/DESCRIPTION	VEGETATION	LAND USE	COMMENTS
Active Beach (Qsa)	- Variable thickness (2–6 m) and width (2-25 m) - Composed of medium to coarse, unconsolidated, poorly sorted calcareous sand - Sediments composed of reworked marine deposits and minor aeolian sands - Occasional boulders representing storm deposition	**1** Consolidation – Unconsolidated Slope – Gentle to moderate Unit thickness – 2-5 m Vegetation cover – Nil Runoff potential – High Primary erosion source – Wind and wave erosion	Nil	- Predominantly pedestrian use - Minor vehicular use for boat launching	-Present in all study zones - Turtle nesting in the northern regions of area G - Large regions of active beach are fringed by the strongly lithified Tantabiddi Member. - Periodic high level erosion through storm activity
Bundera Calcarenite - Tantabiddi Member (Qbtr)	- Outcrops predominantly between low and high tide, minor outcrops inland with only surface characteristics cropping out - Thickness up to 30 m - Composed of coral reef assemblage in lower member - Composed of intertidal calcareous sands in upper member	**2 and 4** SCI variable according to outcrop location - Coastal outcrops: 2 (99%) - Inland outcrops: 4 (1%) Consolidation – Well consolidated Slope – Gentle to steep Unit thickness – up to 30 m Vegetation cover – nil Runoff potential – Low to high Primary erosion source – Coast: waves; Inland: wind	Nil	**Coastal outcrop** - No vehicular use - Pedestrian access for fishing **Inland outcrop** - Substrate for access tracks in few localities	- Present in all study zones - Outcrop sequence from reef deposition to sand sheet deposits not always present. Commonly only horizontal upper surface outcrops exposed inland.

UNIT	DESCRIPTION	SUBSTRATE CAPACITY INDEX/DESCRIPTION	VEGETATION	LAND USE	COMMENTS
Modern Ephemeral Channel (Czc)	-Constituents vary from red clayey sand to pebbles and boulders. -Typically unlithified conglomerate, analogous in composition and environment of deposition to the Mowbowra Conglomerate	**3** Consolidation – Poor Slope – Gentle to moderate Unit thickness – 0.5-6 m Vegetation cover – moderate to high Runoff Potential – High Primary erosion source – Alluvial activity	Acacias to low grassland and medium scrubland	Dominantly in Areas F and G **Area F**: Campsites at North Mandu, Pilgramunna, Lakeside, T-bone Bay, Tulki Beach Car parks at Varanus, Trealla, South Mandu, Yardie Creek **Area G:** Tantabiddi Boat Ramp	- Subject to flooding during storm events and tropical cyclones - Mobile sediments
Alluvial Fans and associated claypan terrain (Cza)	-Alluvial Fans: Clayey red calcareous sands with pebbles up to 5 cm diameter. -Constituents predominantly originate from Tertiary limestone units of the Cape Range Group and transported through fluvial activity though the Late Pleistocene to the present. -Claypan Terrain: In the vicinity of alluvial fan terminus (including relict alluvial fans), typically fine grained sandy clays.	**3** Consolidation – Poor to moderate Slope – Gentle Unit thickness – 1-12 m Vegetation cover – Moderate to high Runoff potential – Alluvial fans: moderate; Claypans: Low Primary erosion source – Alluvial activity and minor wind	Alluvial Fans: Highly variable; Acacia coriolis groves, open grasslands, low to medium scrublands Claypan Terrain: Low grasslands	High land use for day use sites and access tracks in all study zones. Campsites located in Area F at North Mandu, Pilgramunna, Lakeside, T-bone Bay and Tulki Beach	-Extensive coverage throughout study region -Susceptible to flooding due to storm events and tropical cyclones

UNIT	DESCRIPTION	SUBSTRATE CAPACITY INDEX/DESCRIPTION	VEGETATION	LAND USE	COMMENTS
Longitudinal Dunes (Qe)	-Variable lithology, predominantly quartz and carbonate sediments. Areas proximal to coast have a higher percentage of carbonate grains than further inland	**3** Consolidation – Poor to moderate Slope – Moderate to steep Unit thickness – 5-30 m Vegetation cover – Sparse to high Runoff potential – Moderate to high Primary erosion source- Wind	- Open shrubland and grassland including spinifex and heath	Units present only in areas E, G and H - Low level land use, access tracks and minor quarrying in area H	Extensive coverage in the south of the study region inland of anticlinal dome
Bundera Calcarenite - Tantabiddi Member with alluvium cover (Qbt)	- 0.1-5 m thick alluvium cover composed of red clayey calcareous sands originating from Tertiary limestone's of Cape Range Group Below alluvium cover, Last Interglacial Limestone palaeo-reef/lagoon system, composed of coralgal reef deposits and coarse calcareous sands	**4** Consolidation – Moderate Slope – Gentle to moderate Unit thickness - Alluvium: 0.1-5 m; Limestone: 1-7 m Vegetation cover – Sparse to high Runoff potential - moderate Primary erosion source – Alluvial activity and wind	Heath, spinifex, low scrublands and Acacia groves	Very high land use in all study zones. - Land use includes access tracks, day use sites and camping grounds	Most extensive unit in the study area
Bundera Calcarenite - Aeolian Member (Qbe)	-Heavily calcretised quartzose grainstone. -Medium to large scale cross bedding in minor outcrops where fabric is preserved -Palaeo-shoreline to Aeolian deposits -Snaking morphology along coastal plain in Areas E, F and G	**4** Consolidation – Well consolidated Slope – Moderate to steep Unit thickness – 1-8 m Vegetation cover – Sparse Runoff potential – Moderate to high Primary erosion source – Alluvial activity, wind	Spinifex and low grassland dominant	Minor use, access tracks occasionally cross unit	Thermoluminescent dating in progress, age? 118 –50 Ka BP.

UNIT	DESCRIPTION	SUBSTRATE CAPACITY INDEX/DESCRIPTION	VEGETATION	LAND USE	COMMENTS
Bundera Calcarenite - Mowbowra Conglomerate Member (Qm)	-Constituents vary from red clayey sand to pebbles and boulders. -Strongly lithified conglomerate, analogous in composition and environment of deposition to modern ephemeral channel deposits	**4** Consolidation – Well consolidated Slope – Moderate to very steep Unit thickness – 1-15 m Vegetation cover – Sparse Runoff Potential – Moderate to high Primary erosion source – Alluvial activity	Nil	Minor outcrop - Walk trails at Mandu Gorge	Diachronous, interfingering with Tantabiddi Member–Relict alluvial deposits -Outcrop more frequent on Eastern Coastal Plain (Wywroll, 1993)
Bundera Calcarenite - Jurabi Member (Qbj)	-Coralgal reef deposits, minor calcarenite. High proportion of coralline algae, coral, foraminifera and molluscs (bivalves and gastropods) -Predominantly formed in shallow marine environment -Typically recrystallised	**5** Consolidation – Well consolidated Slope – Gentle to cliff Unit thickness – 8-12 m Vegetation cover – Low to moderate Runoff potential – Moderate to high Primary erosion source – Alluvial activity	Sparse grassland, spinifex and sporadic scrubland coverage	Walk trails and minor access track development in zones E, F and G	-First terrace member above coastal plain -Extensive, discontinuous outcrop
Tulki Limestone (Tt)	-Typically recrystallised red to yellow nodular bedded foraminiferal packstone -Local low angle cross bedding	**5** Consolidation – Well consolidated Slope – Gentle to cliff Unit thickness – 95 m Vegetation cover – Sparse Runoff potential – High Primary erosion source – Alluvial activity	Minor acacia and low shrublands typically in shallow sloping areas where soil has developed	Minor access through range, 4WD access tracks only	Crops out extensively where terraces are not well preserved in Area G, source rock of coastal plain alluvial deposits

UNIT	DESCRIPTION	SUBSTRATE CAPACITY INDEX/DESCRIPTION	VEGETATION	LAND USE	COMMENTS
Exmouth Sandstone (Qx)	-Well sorted, fine to medium grained, quartzose calcarenite with large scale cross bedding and occasional calcrete soil intercalations	**5** Consolidation – Well consolidated Slope – Gentle to cliff Unit thickness – 8.5 m Vegetation cover – Sparse Runoff potential – High Primary erosion source – Alluvial activity	Minor acacia and low shrublands typically in shallow sloping areas where soil has developed	As for Tt	-Common lithology of upper Terrace Members, source rock of coastal plain alluvial deposits
Vlaming Sandstone (Tv)	-Well-sorted medium grained quartzose calcarenite. -Calcreted soil units common -Large scale, steep cross beds common	**5** Consolidation – Well consolidated Slope – Gentle to cliff Unit thickness – 38-65 m Vegetation cover – Sparse Runoff potential – High Primary erosion source – Alluvial activity	As for Qx	Access only in Area G, Lighthouse lookout and caravan park region	-Moderate level of outcrop, in ranges, -source rock of coastal plain alluvial deposits
Pilgramunna Formation (Tp)	-Well-sorted, well-rounded, fine to very coarse-grained quarzose calcarenite (grainstone) to calcareous quartz arenite with interbedded lenses of muddy calcarenite (packstone and coralgal boundstone. -Channel fill sequences and rare low angle cross bedding	**5** Consolidation – Well consolidated Slope – Steep to cliff Unit thickness – 20-30 m Vegetation cover – Sparse, minor soil cover Runoff potential – High Primary erosion source – Alluvial activity	As for Qx and Tv	Access only in Area G for walking in the vicinity of Lighthouse lookout	-Crops out primarily in Area G

7 NATURAL HAZARD RISK AND ACTIVITY NODES

The concept of risk combines an understanding of the likelihood of a hazardous event occurring, with an assessment of its impacts on the natural and built environment. Estimation of risk is an uncertain science because it involves forecasting future events whose temporal and spatial occurrence is commonly largely unknown. However, analysis of past records of hazardous events enables a broad understanding of which events pose the most risk and when and where they have the greatest impacts.

Based upon data from the Bureau of Meteorology (1999), tropical cyclones are the most frequent natural hazard in the study region, passing every 2 to 3 years. Geoscience Australia (2004) has defined the coastline as being a moderate tsunami risk zone, with occurrence up to every 5 years (Collins *et al*, 1999). Furthermore, the relatively low relief of many coastal areas may be influenced by potential sea level rise. Projections of the IPCC (1996) for the next century have been used in risk analysis.

As discussed in 1.3.6, the impact of the defined hazards depends on specific process characteristics, the elements exposed and the associated vulnerability of each element to damage or change as a result of the event (Geoscience Australia, 2004). The entire region is potentially exposed to tropical cyclones, tsunamis and projected sea level rise. However, in analysis of the related impacts, it is those affecting major activity nodes to the highest degree and potentially causing the most financial burden in terms of infrastructure repair that are of primary interest to land managers and hence the focus of risk assessment.

7.1 Tsunami Risk Analysis

In risk analysis, the magnitude of the wave at the shoreline and the roughness of the surface are the major factors controlling inland inundation, with coastal topography also being an influencing factor.

Nott and Bryant (2003), Bryant (2002) and Kelletat and Scheffers (2003) have analysed boulder and lag deposits in various localities along the coastal plain of Cape Range Peninsula, indicating maximum palaeo-tsunami heights, otherwise referred to as run-up (H), have reached 6 m. Furthermore, Gregson *et al.* (1978) report a maximum run-up of 6 m related to a major earthquake in Indonesia on August 19th, 1977.

For the purpose of modelling the potential inland extent of tsunami events, this maximum height variable enables characterisation of the optimal impacts to ensure land managers can account for the worst-case scenario in sustainable planning strategy development.

A vast degree of spatial variability in regard to the inland extent of inundation is possible, and primarily a function of coastal morphology and wave characteristics.

Initial wave magnitude is greatest in coastal areas adjacent to passes in Ningaloo Reef, where wave attenuation is minimal and refraction concentrates kinetic energy. Alluvial processes have historically been responsible for development of passes in the Ningaloo Reef. As the largest systems have tended to retain their approximate spatial distribution throughout the Quaternary, modern channels commonly lie adjacent to these reef passes. The combination of minor wave attenuation, refraction related concentration and the low topography associated with channel incision through areas otherwise characterised by dunes is responsible for these zones being defined as optimal risk localities.

Upon analysis of current tourism nodes, it is evident that many of the most popular camping destinations along the coastal margin are high-risk zones. These areas are defined as; Tantabiddi Boat Ramp (N: 7573800; E: 807790), Pilgonaman Creek (N: 7542950, E: 794500), Yardie Creek (N: 7528600; E: 789800), Mandu Mandu Creek (N: 7547900, E: 797600), T-Bone Bay (N: 7561700, E: 801600) and Lakeside (N: 7560650, E: 800800).

Risk calculation methodology is outlined in 1.3.6. Considering Manning's surface roughness coefficient (n) is between 0.035 and 0.060 for ephemeral streams on plains with brush to low tree coverage, these values are classified as end members of this variable.

Also, considering H (run-up) ~ H_0 along low relief coastline, it is assumed that $H_0 = 6$ m.

Therefore, $X_t = \dfrac{0.06\,(6)^{4/3}}{(0.035)^2} = 534 \text{ m}$ and $X_t = \dfrac{0.06\,(6)^{4/3}}{(0.060)^2} = 182 \text{ m}$

Pilgonaman Creek hosts one of the areas most popular campsites and is used as an example in Figure 7.1 to represent the risk envelope defining the inland extent of inundation associated with the maximum projected tsunami capable of reaching the region.

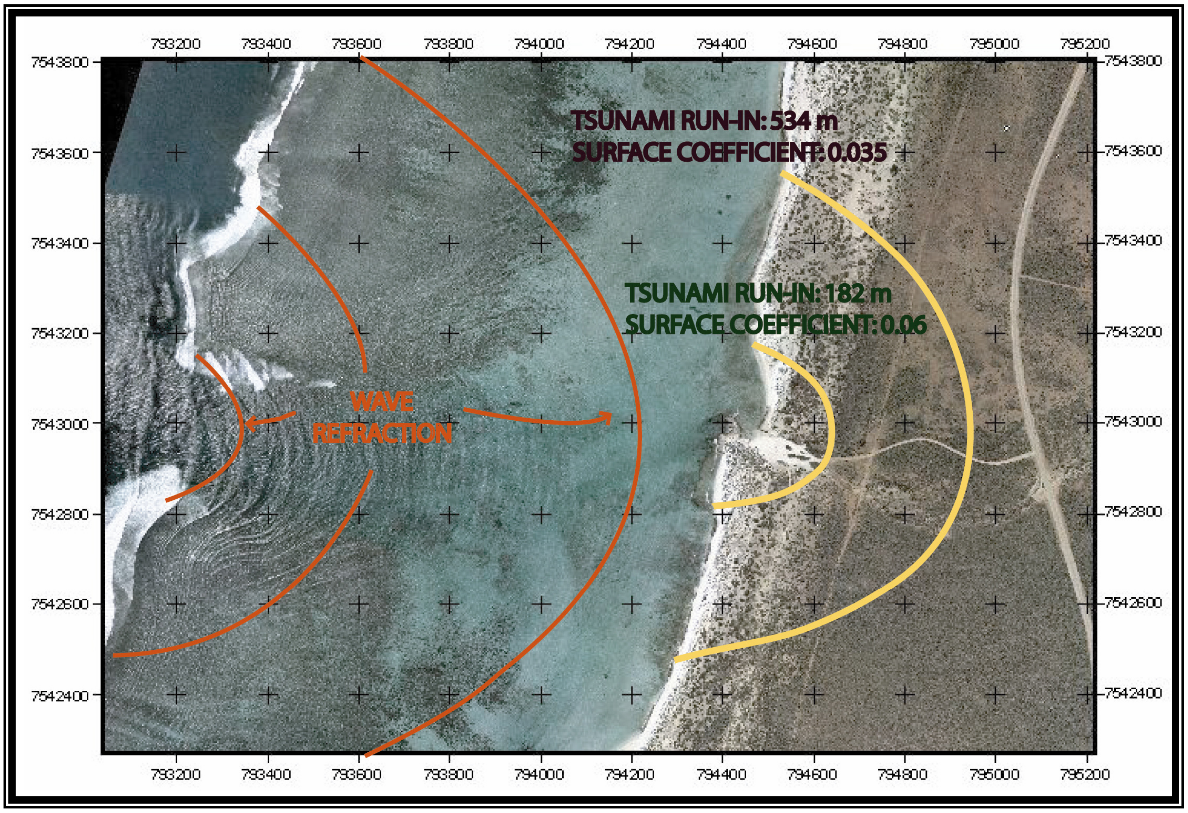


Figure 7.1 Potential tsunami run-in extents at Pilgonaman creek, western Cape Range Peninsula.

7.2 Tropical Cyclone Risk Variables

There are three components of a tropical cyclone that combine to make up the total hazard; storm surge, rainfall and associated flooding and intense winds (Harper *et al.*, 2003). Each of these controls is capable of having diverse impacts upon the natural and built environment and, although interrelated, are best dealt with individually to assess the specific potential impacts.

The focus of this study is to assess the potential impacts of storm surge as this phenomenon has a major influence on coastal morphology and lithology, affecting low lying areas in the vicinity of the coastline commonly used for camping.

Although flooding events have significant impacts on landscape, identified through analysis of pebble layers in alluvial fan deposits, the temporal relationship between these layers and the spatial extent of specific depositional episodes is not known. Furthermore, past impacts of flooding events related to tropical cyclones have not been documented sufficiently to enable the analysis of risk posed due to this phenomenon. For this reason, the influence of this element is not delineated and it is recognized that further research into flooding and the overall combination of this process and storm surge effects is required to aid in risk mitigation. Data currently available regarding flooding is summarized in Appendix 4.

Records of damage to the natural and built environment from strong winds associated with tropical cyclones has been documented and accounted for in management strategy development and will not be addressed in this study as mitigation strategies are already in place and primarily involve sustainable engineering strategies (Western Australian

Planning Commission (2003). Wind related impacts and associated risk mitigation strategies are outlined in Appendix 5.

7.2.1 Storm Surge Risk Analysis

The many controls defining storm surge characteristics at landfall make it difficult to fully understand the possible risk of damage at any one location. However, it is possible to resolve the variables into two categories; cyclone and tidal characteristics and natural and built environment characteristics, as outlined in Table 7.1.

Table 7.1 Variables to consider in delineation of storm surge risk (adapted from Coch, 1994).

NATURAL AND BUILT ENVIRONMENT	CYCLONE AND TIDAL CHARACTERISTICS
• Coastal topography and configuration • Offshore reef morphology • Substrate capacity • Infrastructure (eg. Toilets, waste disposal units, shade houses, information boards, solar power units) • Infrastructure physical characteristics (eg. Strength to withstand impacts, substrate built upon)	• Central pressure of cyclone • Path of cyclone • Wind velocity in various zones of cyclone system and related spatial variability in surge height • Velocity of total cyclone migration • Tidal stage

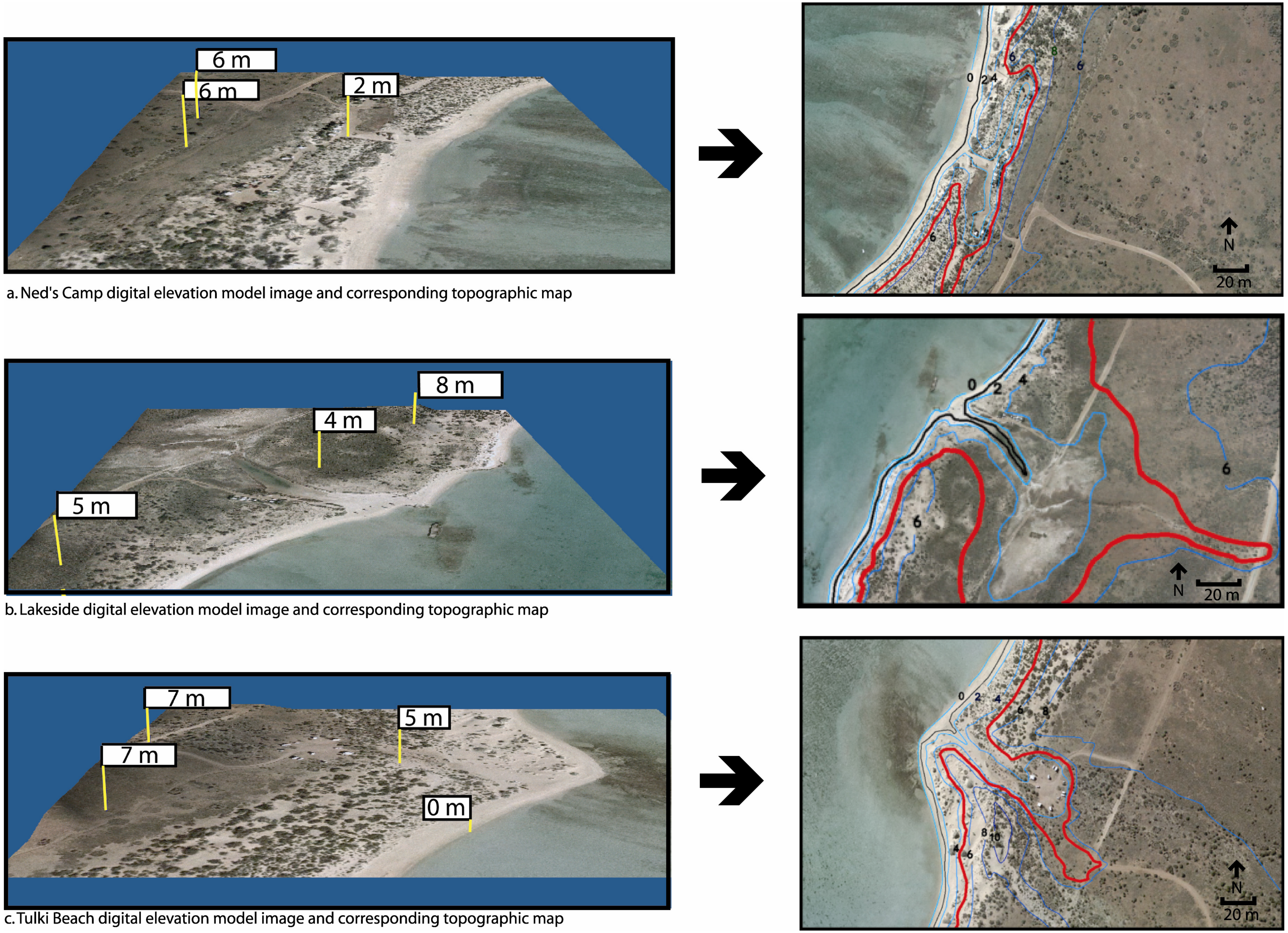
In development of a model to ascertain the maximum landward extent of storm surge it is necessary to consider the optimal potential surge height at the coast. This is related to cyclone and tidal characteristics and offshore reef morphology, with coastal areas in the lee of reef passes prone to the greatest magnitude surges as the wind produced wave component is greatest in this region due to less attenuation by the reef tract (Collins *et al*., 1999).

To establish this height variable, characteristics and impacts of 41 tropical cyclones recorded by the Bureau of Meteorology since 1916 were analysed. The largest recorded surge event in the region is that of Tropical Cyclone Vance, which passed the area in 1999. The maximum surge height was recorded at 4 m for this event, which occurred at mid-tide (Collins *et al*., 1999; Barrett, 2000). Upon consideration of spring tide height being 1.8 m, 0.9 m must be added to this figure for the purpose of defining the potential surge height and therefore, an optimal height of 4.9 m is defined.

Upon establishment of maximum storm surge characteristics, analysis of coastal and offshore Ningaloo Reef morphology enables determination of specific land use areas susceptible to inundation.

As reef passes often lie adjacent to modern low elevation alluvial systems, the combined impact of optimal surge height and low topography places these areas at the most risk to inundation. Furthermore, alluvial systems are subject to the added impact of precipitation related flooding and although there are no quantitative figures for the impacts of this phenomenon, it must also be recognised in risk assessment.

Assuming maximum surge height can reach 4.9 m above mean low tide, areas below this elevation are subject to inundation if not protected to seaward by more elevated land. Determination of coastal topography in the vicinity of land use nodes situated in alluvially dominated areas has enabled classification of the landward extent of inundation from the optimal storm surge currently theorized to be capable of developing in the region. Topographic maps of these areas and the associated contour of surge influence are illustrated in Figure 7.2 and 7.3.

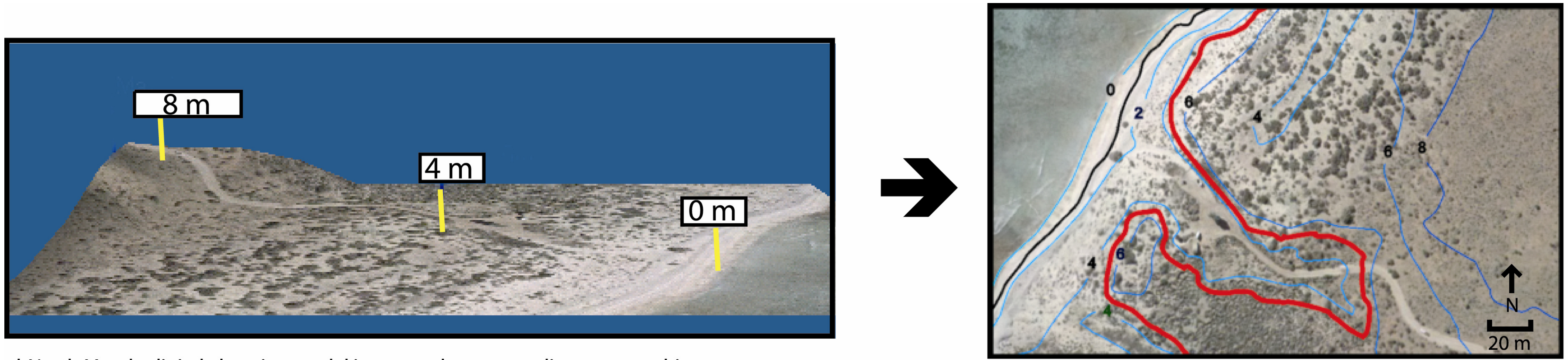


a. Ned's Camp digital elevation model image and corresponding topographic map

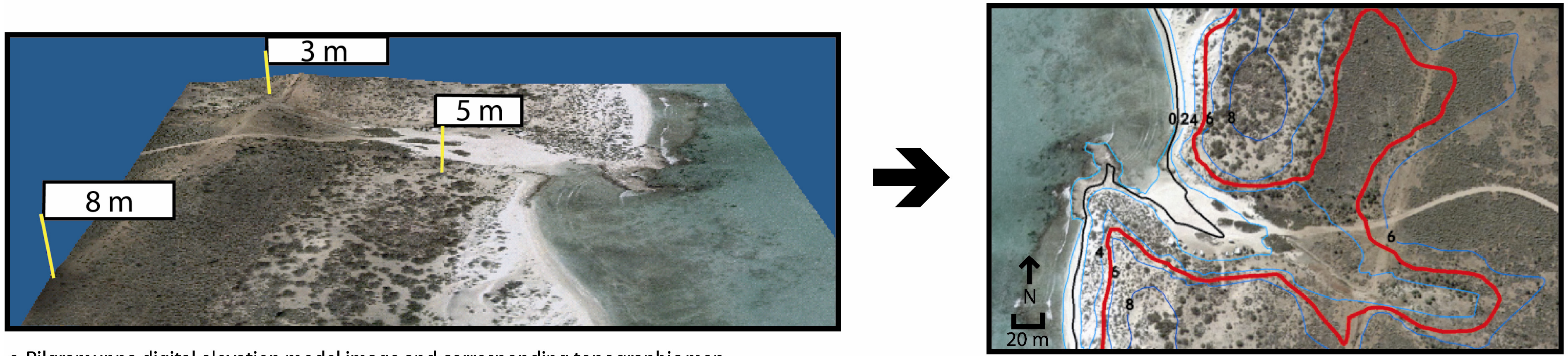
b. Lakeside digital elevation model image and corresponding topographic map

c. Tulki Beach digital elevation model image and corresponding topographic map

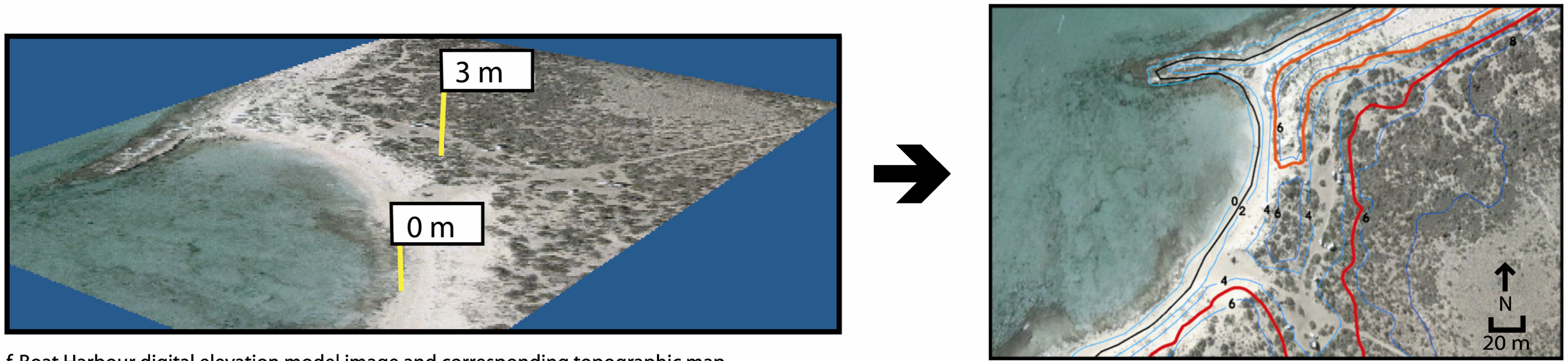
Figure 7.2 Storm surge and projected sea level rise risk zones a, b and c. Maximum inland extent of storm surge (red contour) and maximum inland extent of sea level rise (black contour)



d. North Mandu digital elevation model image and corresponding topographic map



e. Pilgramunna digital elevation model image and corresponding topographic map



f. Boat Harbour digital elevation model image and corresponding topographic map

Figure 7.3 Storm surge and projected sea level rise risk zones a, b and c. Maximum inland extent of storm surge (red contour) and maximum inland extent of sea level rise (black contour)

7.3 Projected Sea Level Rise Risk Analysis

Sea level rise is currently an issue being addressed in land management regimes and knowledge of the optimal extent of terrestrial inundation due to this phenomenon is required to ensure sustainable development of tourism access nodes.

Although there is no conclusive evidence to confirm predicted sea level changes, the IPCC (1996) have outlined possible scenarios for the next century, as outlined in 3.1.4

The impacts of the highest scenario, defined as sea level reaching +0.93 m by 2100, have been assessed as this ensures infrastructure degradation risk is mitigated to the greatest possible degree.

Coastal areas with the lowest elevation are subject to the most inundation. As these areas are typically in the vicinity of alluvial systems, contours of potential inundation extent have been defined for these regions as illustrated in Figures 7.2 and 7.3.

Models of sea level rise impacts were based upon modern shoreline morphology and it is essential to recognize coastal change due natural variations in accretion and erosion may lead to spatial variations of impacts in the future from that predicted in the models defined in this assessment. In view of this fact, it is important that continued monitoring in the area be undertaken to minimize the future impacts of sea level rise.

8 Potential Land Degradation and Tourism Nodes

8.1 Land Use Classification and Factors controlling Risk

All current public land use nodes in the study region have been analysed to derive potential anthropogenic related degradation risks, where risk is defined as;

Risk = Hazard + Exposure + Vulnerability

The land use type as outlined in Appendix 1 defines hazard. Exposure is recognised as the potential magnitude of the area affected by land use, which has been determined by analysis of over 400 sites and classified as reaching an average radius of 15 m from site boundaries. Furthermore, vulnerability is defined as the characteristics of a land unit to withstand impacts, which is further delineated in classification as substrate capacity.

8.2 Risk Analysis

Spatial assessment of the potential degradation risk posed by anthropogenic related activities is based upon field observations and subsequent mapping of SCI, exposure and land use types. Arcview Spatial Analyst 1.1 was used to define the exact combination of each variable for every 25m^2 area over the entire study region. Each of these 25 m^2 cells has been classified independently according to the scheme outlined in 1.3.5, Table 1.2.

Risk assessments for tourism nodes defined as current and projected major use areas by the Western Australian Planning Commission (2004) are of most interest for land managers and have therefore been chosen as sites for hard copy mapping as illustrated on maps 3 and 4. Specific geological characteristics of each risk zone are defined on these maps to further define typical lithology with low substrate capacity. Furthermore, the primary land use purposes have been detailed in order to acknowledge the current potential magnitude of land use and related degradation.

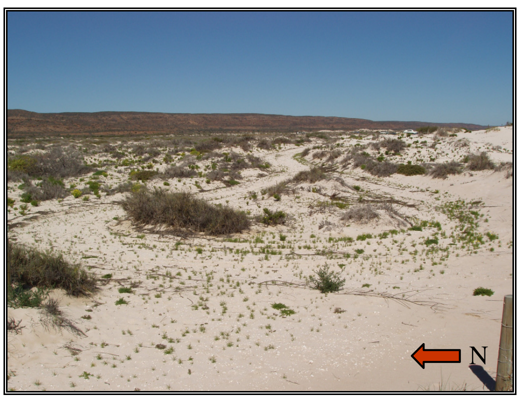
Camping grounds and day use sites are primarily located in Holocene dune sequences and alluvial systems in the vicinity of the coastline. These areas are commonly characterised by poorly vegetated, unconsolidated mobile dunes with a substrate capacity index of 1 (SCI-1). Thus, these areas have been classified as very high to extreme risk zones depending upon the magnitude of potential land use. Examples of these areas are illustrated in Figure 8.1.

Coastal beach ridges with a high percentage of vegetation coverage are at less risk to land use related degradation assuming removal does not occur. These land units are classified as possessing an SCI of 2, and are classified as high-risk zones.

Landward of coastal dune sequences, land units typically have a medium to high substrate capacity (SCI 3-5), consisting of a consolidated limestone foundation overlain by a thin to non-existent layer of alluvium and commonly high vegetation coverage. The level of potential degradation to these units is reduced due to the increased erosion resistance afforded by the vegetation cover and consolidated underlying substrate, and hence these regions have typically been classified as moderate to low risk zones.

a. Tulki Beach, situated adjacent to an Ephemeral channel and beach ridges

b. North Mandu, located in channel surrounded by Holocene dunes



c. Turquoise Bay. Dune degradation resulting from vehicular use in unlithified dunes

e. Yardie Creek. An inter-dunal swale hosts a popular day use site

e. Lakeside. Located between Holocene dunes and an ephemeral channel

f. T-Bone Bay. Situated in an inter-dunal swale subject to flooding (Horizon = 200m)

Figure 8.1 Tourism activity nodes located in regions with a high potential degradation risk

9 DISCUSSION

The geology, geomorphology and physical processes in the north and western regions of Cape Range Peninsula have been delineated in this research. The outcomes of spatial analysis of these features have enabled assessment of degradation risks due to anthropogenic impacts and natural hazards.

The regional geology is characterised by Tertiary uplifted anticlines and low-lying coastal plains. Cape Range Anticline reaches an elevation of 314 m, extending along the inland area of the peninsula, and is the source of widespread alluvial fan deposition upon the adjacent coastal plains (Hocking, 1990).

Subsequent to cessation of tectonic activity in the late Tertiary, eustatic fluctuations have played the primary role in coastal evolution. The Late Pleistocene Interglacial, 121-128 ka BP, was characterised by +3 to 4 m sea level and climatic conditions were suitable for reef colonisation upon Tertiary limestones. These reef deposits have been preserved as the Tantabiddi and Mowbowra Members of the Bundera Calcarenite and form the foundation of the modern coastal plain. The initial morphology of these Pleistocene units dictates modern coastal accretion by controlling Holocene patterns of accumulation, leading to formation of localised nodes and anti-nodes of sedimentation.

Subsequent climate changes and associated complex interactions between coastal processes are responsible for the evolution of the unique landscape of the coastal plain and development of Ningaloo Reef, Australia’s longest fringing reef.

6 stages of Late Pleistocene and Holocene climate changes and associated eustatic fluctuations have been recognised as primary influences on Quaternary coastal plain evolution; 1) The Last Interglacial 2) a possible second phase of the Interglacial highstand (?118 ka BP); 3) an overall regressive phase lasting from 118 to approximately 30 ka BP; 4) a glacial peak between 20 and 30 ka BP; 5) transgression until approximately 5.3 ka BP, upon which a highstand was reached; and, 6) a regressive phase extending to the present.

Specific geological characteristics of each area have been mapped at a resolution of 1:500 to 1:2000 using GIS to define the spatial layout of units. Upon completion of this process it was evident that geological and geomophological responses to each of these phases are variable along the extent of the coastline.

The coastal plain in Areas E, F and G is bordered by Cape Range Anticline and is subject to similar alluvial processes sourced from this region. Ephemeral channels and associated alluvial fans are the dominant features of the inland region of the plain. Sporadic outcrops of the Tantabiddi Aeolian Member, representative of the second stage, are surrounded by alluvium and are the primary elevated feature of the inland plain.

The geomorphologic and geologic setting of Area H is somewhat different to Areas E, F and G. This area is situated to the northeast of the anticline and although the Tantabiddi Member defines the foundation of the region, flooding at the mid-Holocene highstand has resulted in erosion and burial of earlier Pleistocene stratigraphy and supratidal saline flat development.

Fringing beach ridges and modern foredunes, formed in stage 6, dominate the coastal geology and geomorphology in all study areas. The width of beach ridge fields is a function of initial geomorphology of the underlying Tantabiddi Member, with seaward accretion greatest in areas of sedimentation nodes.

Further delineation of substrate characteristics, accounting for vegetation coverage and geomorphologic features in addition to lithology, has revealed that the coastal dune fringe is most susceptible to impacts from natural and anthropogenic sources, as this region is typically composed of unlithified calcareous sands, with a moderate to low vegetation cover and high erosion potential.

All tourism based activity nodes have been mapped to determine the risk of degradation posed in the vicinity of each site. In classifying spatial variations by risk, the substrate capacity upon which each site is situated and the potential area impacted are the primary controls.

Areas of land use characterised by a moderate to high substrate capacity have been classified as low to moderate risk zones, whereas regions of low substrate capacity are deemed to be at high to very high risk.

The degradation risks associated with all land use sites were analysed and calculated using Arcview Spatial Analyst. For the purpose of providing useful data to land managers, hard copy risk maps for all major activity nodes have been produced. It is evident that the majority of land use sites are at high to very high risk of degradation as they are situated within the low substrate capacity, high-risk coastal dune fringe.

In addition to an assessment of the risk of degradation posed by land use, the potential impacts to activity nodes of natural hazards have been determined. It is evident that areas with the lowest relief are at most risk of inundation due to tropical cyclone related storm surge, tsunami run-in and projected sea level rise. Upon analysis of the topography in the vicinity of all major tourism nodes, it has been revealed that areas in ephemeral channels typically have the lowest elevation and are hence at the greatest risk of inundation. The potential inland extent of impacts related to storm surge and sea level rise have been documented for the 6 highest risk zones; Ned's Camp, Lakeside, Tulki Beach, North Mandu, Pilgramunna and Boat Harbour. Furthermore, it has been revealed that tsunami run-in can potentially reach 534 m inland along the western coastal plain of Cape Range Peninsula. This has been ascertained through production of a model delineating surface roughness coefficients and optimal wave characteristics in the western coastal region landward of Ningaloo Reef.

Risk analysis of the potential impacts on activity nodes due to land use and natural hazards has provided useful information regarding the sustainability of current tourism activity node positioning, which is a vital consideration in the development of future land management strategies.

10 CONCLUSIONS

This study has served to provide evidence regarding physical processes that are responsible for coastal geomorphologic and geological evolution. Use of GIS has served to provide information about the spatial distribution of units and their respective substrate characteristics, enabling analysis of the potential degradation risk posed by tourism related activities in the area. Furthermore, an understanding of the natural hazards that may influence the coastal plain has been gained and the risk of impacts in the vicinity of activity nodes delineated.

The primary outcomes are as follows;

- The inland region of Cape Range Peninsula is characterised by the north to northeast trending Tertiary Cape Range Anticline. Surrounding this structure, a low relief coastal plain extends to the modern coastline.
- Eustatic fluctuations in response to climate change have been the primary influence on Quaternary coastal plain evolution. 6 distinct phases are recognised to have formed a discontinuous calcareous ridge close to the inland boundary of the plain, extensive alluvium deposition along the extent of the inland plain, longitudinal dunes, supratidal flats and intertidal mangrove swamps, prograded beach ridges, modern foredunes and beaches.
- Substrate capacity (based upon geomorphologic features and vegetation coverage) is typically high along the hinterland of Cape Range Anticline, moderate in areas characterised by a thin alluvium cover and low in Holocene coastal dune sequences.

- Activity nodes are typically situated in coastal dune fields. These nodes are at high risk of degradation, as the substrate in this region is highly susceptible change.
- Tropical cyclones and projected sea level rise present the greatest impact risk in the vicinity of coastal tourism nodes in the lowest relief areas, typically ephemeral channels.
- Tsunami run-in is capable of reaching 534 m inland along the western coastal plain in areas characterised by ephemeral channels or with low foredunes

Geological, substrate capacity and risk maps delineating degradation potential in the vicinity of coastal activity nodes provide a valuable data source for land managers to consider in the development of sustainable natural resource management strategies.

11 RECOMMENDATIONS

- A detailed study of the specific impacts related to the risk zones delineated in this study should be undertaken, with the aim of improving management of these fragile areas in close proximity to the Ningaloo Reef.
- Detailed documentation of plant communities prevalent along the coastal plain, to gain a better understanding of vegetation variations and the role played in coastal dune stability.
- Acknowledgement of the interactivity of oceanic, lagoonal and coastal processes in an overall assessment of coastal characterization in management strategies.
- Further Research regarding Tropical Cyclone related flooding to enable a combined assessment with storm surge and hence delineate the full impact of surges and flooding in the coastal zone.
- Further research of tsunami amplitude maxima and the variety of effects this hazard poses to the coastal zone.
- Development of tourism activity nodes in zones characterised by a higher substrate capacity and at less risk of natural hazard impacts.

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APPENDIX

1. Reasoning for the 15 m envelope around activity nodes in delineation of degradation exposure.

2. Reasoning for the 25 m^2 grid cell size selection in spatial analysis.

3. Natural Hazard Risk Zone Delineation And Limitations

4. Tropical Cyclone Related Precipitation and Impacts

5. Wind Velocity and Impact Associated With Tropical Cyclones

6. Petrographic Descriptions

7. Instructions To View GIS Data

8. Contents Of Accompanying CD Rom

APPENDIX 1

Reasoning For The 15 m Envelope Around Activity Nodes In Delineation Of Degradation Exposure.

Determination of degradation risk associated with land use requires a firm knowledge of areas potentially exposed to impacts.

To delineate this, classification of the various types of land use activities is required and defined as follows;

- Access Tracks - Sealed road
  - 2WD accessible unsealed track
  - 4WD accessible unsealed track
  - Walk trail
- Campsites – Accessible for overnight use
- Car parks – Accessible for day use

Definition of potential degradation is further required. As land use significantly varies spatially on a seasonal and inter-annual basis, the maximum land use impacts currently evident have been used to determine potential risk, allowing for future land use changes. It is recognized that areas with low substrate capacity are subject to the greatest extent of degradation. However, to account for future substrate shifts due to natural processes, it was deemed the most conservative approach to treat exposure in all areas similarly.

Field observations in the vicinity of all campsites, car parks and access tracks coupled with photo interpretation of evident vegetation anomalies and signs of erosion have been used to determine actual degradation extents.

Analysis at 2 km intervals along sealed roads and at 250 randomly selected 2WD unsealed tracks, 4WD access tracks and walk trails revealed land degradation extents range in radius from sites between 3 m in currently low use locations and 15 m in high use areas. Hence, the optimal exposure to degradation has been defined as 15 m.

Assessment of all designated car parks and campsites revealed that degradation varies primarily due to land use magnitude, with low use sites showing signs of degradation reaching only 1 m from site boundaries to 15 m in higher use locations. To account for land use shifts, the exposure envelope was therefore chosen as 15 m.

By placement of envelopes with a radius of 15 m around all access sites, optimal potential exposure has been defined, taking into account future land use changes and hence ensuring sustainable development to the highest possible degree.

APPENDIX 2

Reasoning for the 25 m^2 grid cell size selection in spatial analysis.

5x5 m grid cells have been deemed the most conservative size to use in order to retain accuracy upon conversion of vector substrate capacity and access node maps to raster (grid) format whilst efficiently processing data.

Conversion of substrate capacity maps and access node maps was conducted independently. For each conversion, Spatial Analyst has classified individual cells according to the component of the original map taking up 50% or more of the cell. As cells are 25 m^2, the maximum error in the case of two or more components in one cell is half of this, 12.5 m^2, causing the maximum shift of original boundaries to be 3.34 m. As the ortho-rectified aerial photo used in initial mapping is accurate to 1.7 m and boundary interpretation to within 2-5 m depending upon clarity, conversion of maps to a grid format has maintained mapping accuracy to within the original error margin.

APPENDIX 3

Natural Hazard Risk Zone Delineation And Limitations

In defining areas at risk of exposure from natural hazards, all land use sites were initially acknowledged as potential risk zones. However, the magnitude of financial burden related to degradation was further considered in definition as this is of primary interest to land managers. Sites accessible for overnight use, serviced with a minimum of waste disposal units and toilets were considered the most important zones at risk of degradation as not only infrastructure destruction poses a cost but also diminished accessibility to suitable camp grounds subsequent to these events have longer term tourism impacts than destruction of infrastructure at day use sites.

Limitations in definition of topography are primarily based upon Digital Elevation Model errors. Topography was defined by following lines representing the same elevation. However, elevation figures showed evidence of a slight skew from the actual and had to be corrected manually. This may be responsible for contours being mapped with an error up to ±5 m.

APPENDIX 4

Tropical Cyclone Related Precipitation and Impacts

Three heavy rainfall bands are commonly associated with a tropical cyclone (TC) after landfall. The first is associated with the eye wall core, which extends from 15 to 50 km from the centre. Next, spiral rain bands may extend for several hundred kilometres and can produce torrential rains. An "inverted trough" may also form towards the south of the system causing heavy rains around the periphery of the storm (Harper *et al*, 2003). These rainfall bands are responsible for coastal flooding along alluvial systems that extend along the coastal plain.

Magnitude of precipitation associated with TC's has not been accurately recorded in the past due to a lack of measurement facilities and horizontal to sub-horizontal downpours not being recorded (J. Courtney, pers. comm., 2004). Therefore, the risk to the natural and built environment due to flooding in most areas of the Cape Range Peninsula is poorly understood.

Qualitative analysis suggests alluvial systems and low-lying areas are at the greatest risk of inundation and associated degradation, but the magnitude of impacts in these regions is not well defined. Creek and alluvial fans formed by flooding events (due to the combined impact of rainfall and storm surge) give indications of the influence of precipitation on the natural environment, illustrating the erosion and transport of cobbles, sands and silts that takes place during these events (Barrett, 2000).

As the places most likely to suffer impacts due to flooding are those with the greatest capacity to accommodate water, it is assumed that such locations as fluvial systems will be amongst the highest risk areas. The largest fluvial systems along the western coastal plain of the peninsula are Tantabiddi Creek, Mangrove Creek, Mandu Mandu Creek, Pilgonaman and Yardie Creek. These areas are subject to the greatest hazard due to flooding and as they are all popular tourist sites, present risk for future land use in terms of sustainability of infrastructure.

APPENDIX 5

Wind Velocity and Impact Associated With Tropical Cyclones

Tropical cyclones are accompanied by strong northerly winds, with potentially destructive gusts within 100 km of the centre of the storm (Harper *et al.*, 2003). The strong winds can persist for many hours, or even days, depending on the track of the storm, and can cause widespread building and infrastructure damage. Most of the structural damage caused by tropical cyclones is inflicted by these winds. This damage can be caused directly by the wind or by the debris that it propels (Coch, 1994).

It is the peak gust wind speed (3 second average maximum velocity) which generally causes building damage, whereas the somewhat lower mean, or sustained, wind (10 minute average maximum velocity) is in part responsible for the generation of allied coastal threats such as storm surge (Harper *et al*., 2003).

Extensive research regarding the characteristics and impacts of this variable has been carried out for the northeast coast of Australia. However, little is known about the potential risks to the northwestern regions.

A sustained land wind velocity record of 267km/hr for the Australian continent was experienced across the Cape in 1999, when Tropical Cyclone Vance passed the region (Bureau of Meteorology, 1999).

Extensive structural damage and widespread erosion of coastal dunes prompted concerns regarding the actual risk posed by cyclone related winds.

However, assessment of risk due to this process is difficult to model as it is both spatially and temporally an extremely variable control (Harper *et al*, 2003).

The best mitigation techniques therefore involve development of infrastructure that accounts for maximum winds, aiming to minimize all potential effects.

Variables to be considered in mitigation of wind risk to infrastructure have been outlined by Harper *et al.*, 2003, as summarized below:

- Roof shape and pitch
- Building age and structural integrity
- Terrain 'roughness'
- Shielding or interference from adjacent objects (other buildings)
- Topographic effects on slopes and near the top of hills

Although structural development can account for maximum winds, limitations to risk minimization still exist as buildings can only be developed based upon models of possible 'best design', which is fraught with limitations itself.

In general, risk mitigation requires maximum development of structures that can withstand the severest potential wind impacts.

APPENDIX 7

Instructions To View GIS Data

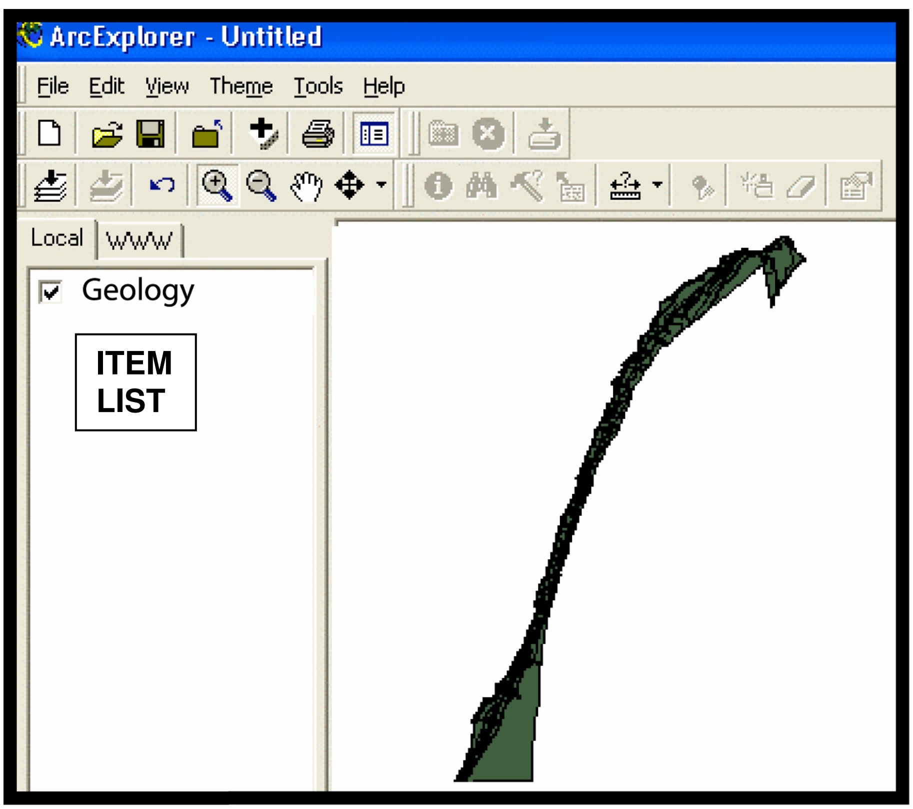
The accompanying CD ROM to this dissertation is designed to allow interactive viewing of the GIS maps created and supply a resource for further study in the region.

How to open Arc Explorer software and view GIS data

1. To open Arc Explorer, double click on the icon 

in the file list.

2. To Add data to the view, press the add theme button 



3. A window titled “Add Theme(s)” will appear.

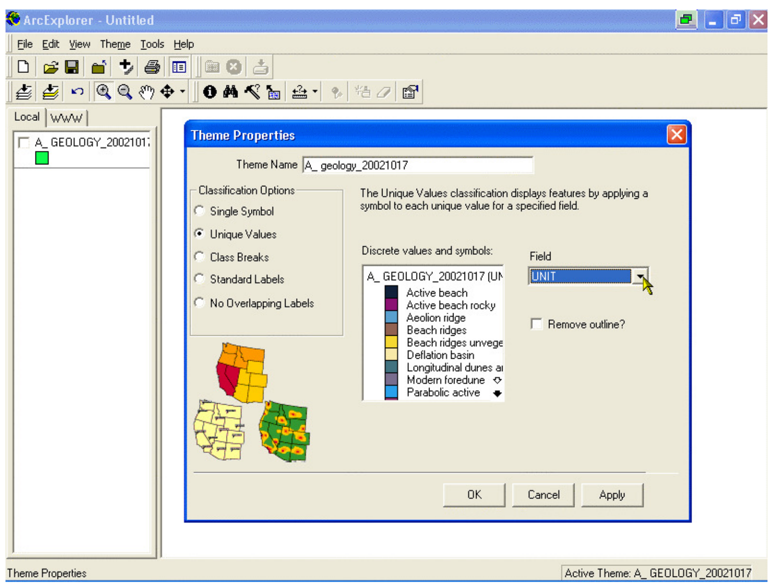
a. Under "Selected folder", double click on the CD.

b. In the top left corner, data type is defined. Click on the arrow on the right side of the box to choose data type, "Shapefiles" to view mapping files.

To view aerial photographs of each area, choose "Supported Images".

4. To make a theme active check the box in the item list. Eg. 

To add a unique colour scheme to delineate different units in geological and substrate capacity maps, double click on the theme in the item list. The following window will appear.



Use "unique value" classification and choose "unit_name" as the field for geology, "subcap" for substrate capacity maps and "access type" for unsealed access tracks.

All other themes are already unique and do not need further classification.

The programme has a very substantial help system should problems be encountered

APPENDIX 8

Contents Of Accompanying CD Rom

Geology and Substrate Capacity;

Geology.shp (this file contains a geological "unit_name" and substrate capacity "subcap" map of the entire study region, to view boundaries of specific areas, shape files within similarly named folders are accompanying as follows;

Areae.shp

Arearf.shp

Areag.shp and

Areah.shp

Geomorphologic features;

Drainage.shp

Trends.shp

Access Nodes;

2wdsealed.shp

unsealed.shp

carpark.shp

campsite.shp

Digital maps of geology in pdf format for each study area can be viewed as follows;

AREAEGEOLOGYPDF.pdf

AREAFGEOLOGYPDF.pdf

AREAGGEOLOGYPDF.pdf

AREAHGEOLOGYPDF.pdf