



Sedimentary processes during the Late Quaternary across the Kimberley Shelf, Northwest Australia.

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Abstract

This study builds on the work of previous mappers and scientists working on the Australian, northwest continental shelf. It addresses margin scale basins and influence of various sedimentary processes across a tropical shelf environment.

The Kimberley and Bonaparte Shelves which are both seaward of the Kimberley Block, north-west Australia, carry a thin Holocene sediment cover. This sediment veneer is punctuated with projecting corallgal reefs, typifying a tropical shaved shelf.

Incising the Kimberley Shelf is the 120 m-deep Penguin Deeps, which today, is a drowned and largely inactive shelf-valley system. This distinctive feature over time, has been flooded with marine waters, subjected to strong tidal currents and operated as an important supply channel for sediment passing westward from the Bonaparte Shelf and into the Browse Sea-valley. At other times, eg. during LGM, the Penguin Deeps was cut off from the sea, and became a seasonally-controlled fluvial and lacustrine canyon.

In the Plio-Pleistocene, the Northwest Shelf platform has corresponded during interglacial sea-level highs to a mainly palimpsest and erosional marine platform with scattered corallgal reefs, and during glacial sea-level lows to a palimpsest and slightly aggradational, arid coastal plain, with relict drainage structures of which are sometimes still visible in the modern bathymetry eg. The Penguin Deeps.

Three subdivisions of the Kimberley Shelf are recognised for the purposes of this study, namely an *inner shelf* 0 - 50 m isobath, corresponding approximately to the offshore edge of the terrigenous inshore sediment prism, a *middle shelf* between 50 and 105 m depth (a current-swept, sediment-starved plain), and an *outer shelf* between 105 and 150 m depth (corresponding to areas of deeper terrace). The Kimberley Shelf terraces are referred to in terms of the estimated depths of their seaward edges, the most widespread ones being the 30 m-, 45 m-, 60 m-, 75 m-, 95 m-, 112 m-, 165 m- and 185 m-terraces. Subsidence rates based on these descending flight of terraces and the regional rates suggests a rate of 15cm/ka at

least for the late Quaternary and figure has been used as an assumption for the workings of this study.

In addition to control by sea-level and subsequent reef development, powerful hydraulic forces which drive currents at speeds of 50-100 cm/s or more, affected sediment transport and deposition in the Penguin Deep area just as they do throughout the Australian marine carbonate provinces. Other such controls include exposure to storms and swells, tropical cyclones, exposure to major ocean currents and tides creating shelves with minimal sediment. These bioclastic carbonate sediments with a low or condensed sedimentation rate are also palimpsest in nature.

Sediment yields from fluvial derived terrestrial inputs for the Holocene are estimated to potentially be $63 \text{ tonnes} \times 10^9$, or 42.28 km^3 . This sediment is deposited and redistributed across the shelf and shelf slope along with a yet to be determined amount of palimpsest material from the Bonaparte Shelf by the range of transport mechanisms and provides another layer of sediment across the Browse Sea Valley.

There have been four main determiners affecting the spatial and temporal distribution of sediments across the Kimberley Shelf. These are changes in oceanic influences, tidal power, fluvial outputs and cyclone frequency. This study clarified these processes and revealed their impact on the sediment distribution over time in the Kimberley Shelf region.

I hereby certify that the work embodied in this thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge contains no material published or written by another person except where due reference has been made.

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For my wife

Fiona

&

my two sons

Hunter Khan 03 . 03 . 1999 -

Tate Maxwell 21 . 02 . 2003 -

List of Acronyms

AMS	Accelerator Mass Spectrometry
BOM	Bureau of Meteorology
BP	Before Present
DGPS	Differential Global Positioning System
ENSO	El Niño/Southern Oscillation
GA	Geoscience Australia
GPS	Global Positioning Satellite
ka	Thousand years
ISP	Inner Shelf Prism
ITF	Indonesian Through Flow
LGM	Last Glacial Maximum
Ma	Million Years
NOAA	National Oceans Atmospheric Administration
SEC	South Equatorial Current
SG	Specific Gravity
SL	Sea Level
SST	Sea Surface Temperature
Sv	Sverdrup ($10^6 \text{ m}^3 / \text{sec}$)
TBO	Tropospheric Biennial Oscillation (TBO)
TWT	Two way time
WD	Water Depth
WPWP	Western Pacific Warm Pool
XRD	X-Ray Diffraction

Chapter 1. Introduction

1.1 Setting

The Australian continent is bounded on three sides by rifted, passive margins, respectively of Palaeozoic to early Mesozoic (western), Jurassic (southern) and Cretaceous (eastern) ages (e.g. Veevers, Powell, and Roots 1991). No post-Gondwana plate boundary traverses its interior. The continent has long been subjected to erosion and is characterised by low relief, small terrigenous sediment yields and deeply weathered, ancient land surfaces (Twidale 1991; Twidale and Campbell 1988; Twidale 1968). Thus, away from its northern collisional border, the younger geological history of the Australian continent comprises gentle subsidence in response to the thermal cooling of its rifted passive margins, together with low rates of terrigenous sediment supply. These circumstances resulted in marine transgression across a peri-continental platform (which became the continental shelf), followed by the increasing development of clear shelf waters that are optimum for the development of carbonate sedimentation, such as the Bonaparte, Sahul and Kimberley Shelves (Figures 1.1, 1.2).

Accordingly, the Australian landmass is today almost entirely encircled by some of the largest marine carbonate provinces in the world. Those of particular interest to this thesis include; the tropical Great Barrier Reef (Maxwell 1973), Torres Strait (Harris 1994), and Northwest Shelf (van Andel 1965), (Heyward et al. 1997) coralgall carbonate provinces in the north. These contrast to the cold temperate bryozoan-brachiopod and foraminiferal provinces in the southeast (Marshall 1980; Marshall and Davies 1976), south (Bone and James 1993; James, and Bone 1992; James, et al. 1994; James et al. 1997, 2000, James and von der

Borch, 1991) and southwest (Collins 1988). In areas of particularly low terrigenous sediment supply, both the warm and cold water carbonate provinces may extend from the outer shelf right in to the shoreline (Gostin, et al. 1988; Harris 1994) (Figure 1.2), and the two climatically-controlled shelf carbonate provinces pass into one another at mid-latitudes ($\sim 27^{\circ}$ S) along both the eastern and western seabords of Australia.

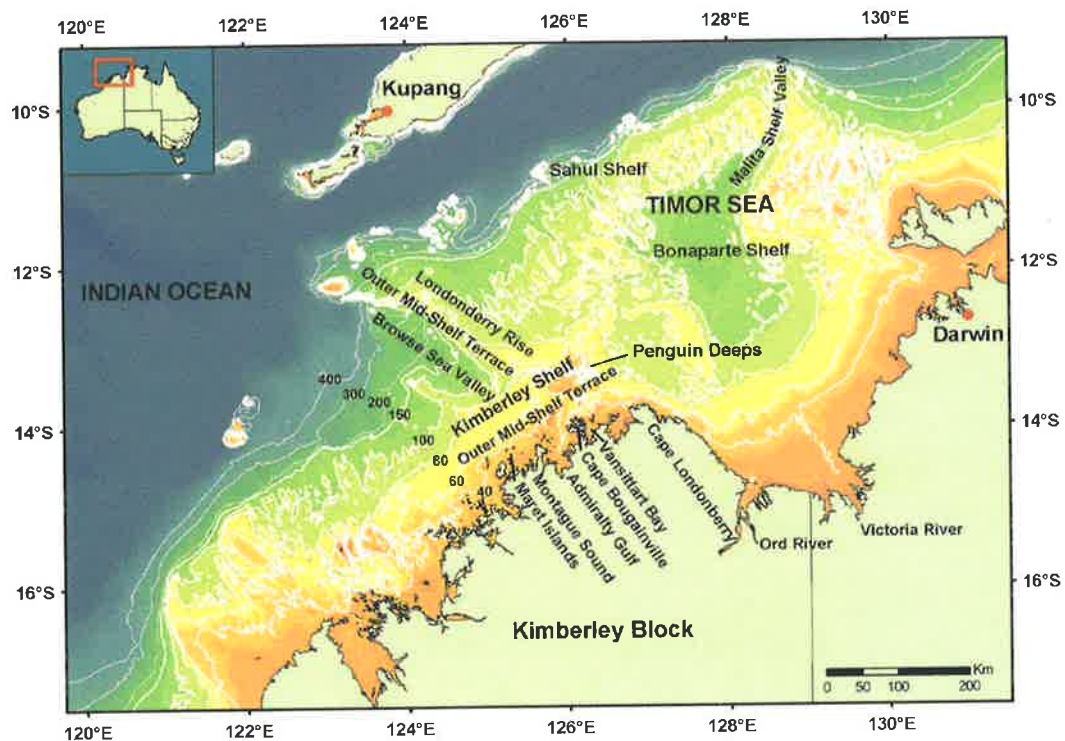


Figure 1.1 Location Diagram of the Bonaparte, Sahul and Kimberley Shelves, Northwest Australia (larger format of this diagram in the enclosures, Enclosure 1.1).

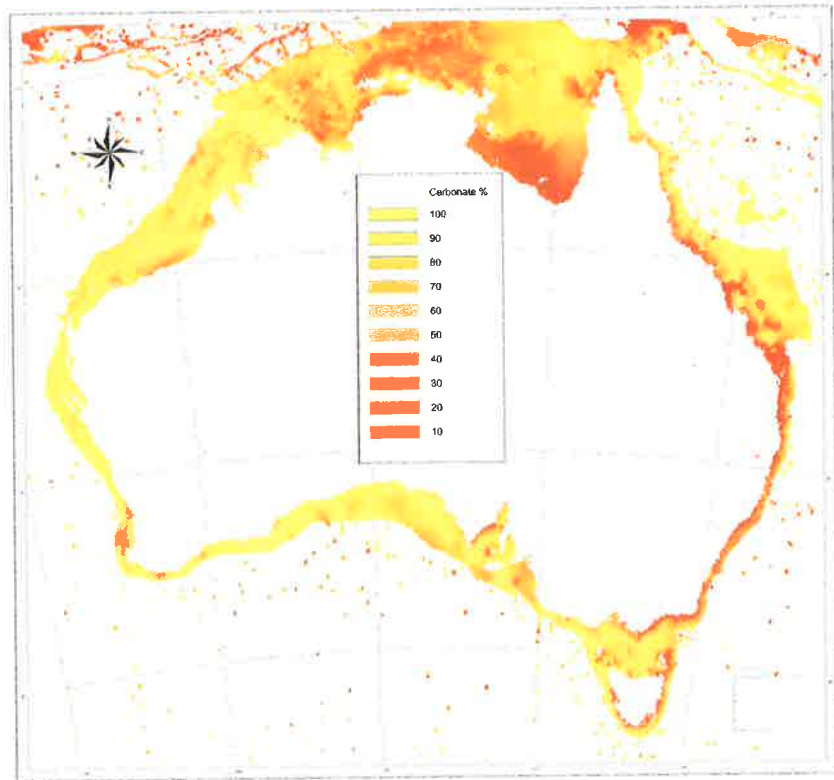


Figure 1.2 Carbonate sediment distribution across the Australian continental Shelves (printed with permission of the CEO Geoscience Australia)

Carbonate sedimentation is particularly susceptible to the influence of changing sea-levels (SL). SL change affects coral reefs by alternately encouraging their growth (during highstands) and destroying them by subaerial exposure (during lowstands).

Temperature	Environment
Cold	Polar
Cool	Temperate
Warm	Tropical

Table 1.1 Temperature and environment nomenclature

Eustasy similarly controls the position and extent of temperate (cool water; Table 1.1) carbonate provinces by alternately drowning and exposing the peri-continental platform upon the outer portion of which they have their maximum (highstand) development. And by varying, concomitantly, the locations at which terrigenous sediment deposition is concentrated.

In addition to control by sea-level, powerful hydraulic forces which drive current speeds of 50-100 cm/s or more affect sediment transport and deposition throughout Australian offshore (carbonate province) waters. Such controls include exposure to Southern Ocean storms and swells (southern margin; James et al., 1994), exposure to tropical cyclones (northern margins; Larcombe et al. 2004), and exposure to major ocean currents (Great Barrier Reef, East Australian Current, Church 1987), Western Australia, Leeuwin Current and Great Australian Bight; (Pattiaratchi 1991), Northwest Shelf, Indonesian Throughflow Current; (Godfrey et al. 1981) and tides (Harris 1994). The precise agent differs from place to place, but never the less, outer shelf carbonate platforms throughout Australia, including between reefs in the tropics, are characterised by the bypassing of sediment along-shelf or over nearby shelf edges, and by the development of a “shaved” outer shelf (James et al., 1994). These are characterised by bioclastic carbonate sediments with a low or condensed sedimentation rate which are often also palimpsest in nature (e.g.; Veevers, and van Andel, 1967, Veevers, 1967 Scoffin and Tudhope, 1985 James et al., 1992, 1997, 2004) such is the case on Australia’s northwest shelf. Thus the Australian continental margins provide important sites for studying the physiographic and sedimentary effects of the glacio-eustatic sea-level changes of the last ~2.5 My (e.g. Raymo, 1992). This research thesis aims to contribute towards the understanding of these whilst focusing on the Kimberley shelf.

1.2 The Sahul Shelf

This research study addresses a part of the circum-Australia carbonate system which is located at the southwestern corner of the large, tropical Sahul Shelf carbonate province (Figure 1.3). The Sahul Shelf forms part of the wider Northwest Shelf of Australia, a peri-continental platform which stretches between Darwin in the northeast and Northwest Cape, further to the southwest and near latitude 20° S. The oceanward edge of the Sahul Shelf is located at relatively shallow depths of 110-130 m, and though bathymetric highs along it today support corallgal reefs, these were destroyed and the shelf edge exposed during late Pleistocene glacial lowstands. The Sahul Shelf coastline is regionally embayed towards the southeast, creating the Joseph Bonaparte Gulf, into the southeastern corner of which flow the Ord, Victoria and other smaller Rivers. These rivers are the main source of terrigenous sediment for the nearby shelf. Bonaparte Gulf waters merge offshore into those of the Timor Sea. Their hydrography is influenced by the effects of the oceanic Indonesian Throughflow Current which flows southwest along and outside of the shelf edge, by extremely strong tidal streams which occur especially around the Admiralty Bay-Kimberley region, and seasonally, by the passage of cyclones.

The Northwest Shelf is underlain in part, by the Bonaparte and Browse Basins (Figure 2.4), which are major petroleum provinces whose origin dates back to the Mesozoic phase of rifting of this part of the Australian continental margin (Purcell and Purcell 1988). The shelf platform itself, however, postdates the filling of these basins, which was completed during the Cainozoic. In the Plio-Pleistocene, the Northwest Shelf platform has corresponded during interglacial sea-level highs,

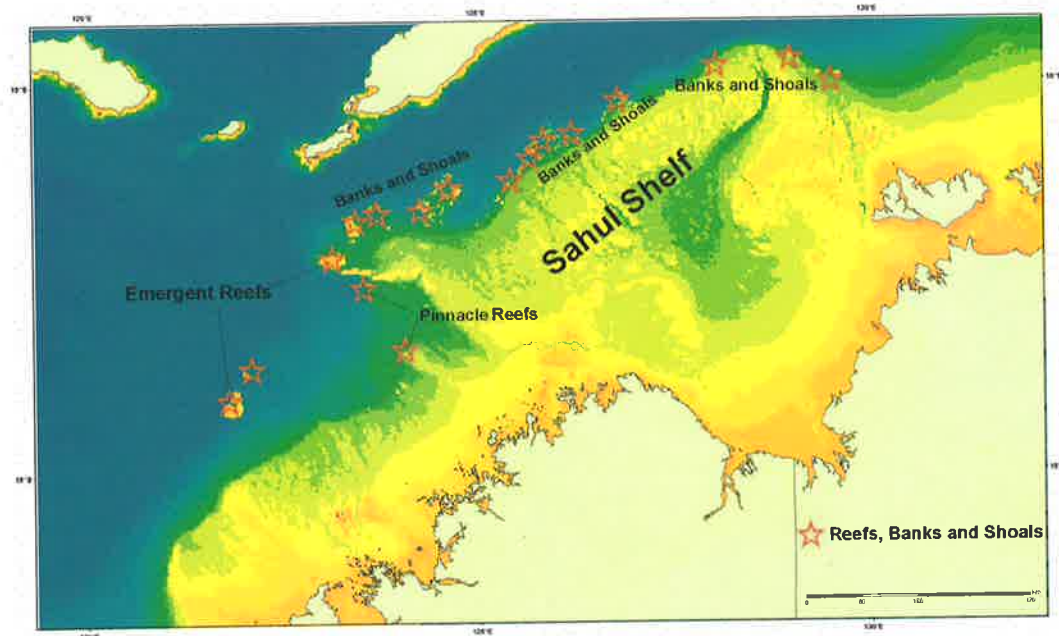


Figure 1.3 The Sahul Shelf and the range of bioherms associated with the shelf edge.

to a mainly palimpsest and erosional marine platform with scattered corallgal reefs, and during glacial sea-level lows, to a palimpsest and slightly aggradational, arid coastal plain, relict drainage structures of which are sometimes still visible in the modern bathymetry (Figure. 1.4). The northwest-running boundary between the Bonaparte and Browse basins lies at the southwest end of the Bonaparte Shelf, where it coincides with a structurally controlled incision across the middle shelf, the Penguin Deep (axial depth up to -120 m). Over the recent past, this channel has clearly exercised a control on both water movement and sediment transport paths, especially during times when sea-level was between -60 and -90 m lower than present day which is also the respective depths of its eastern and western entrances. The late Pleistocene and Holocene processes which have shaped or been guided by the Penguin Deep, together with its adjacent shelf and deeper offshore regions, form the main focus of this research study.

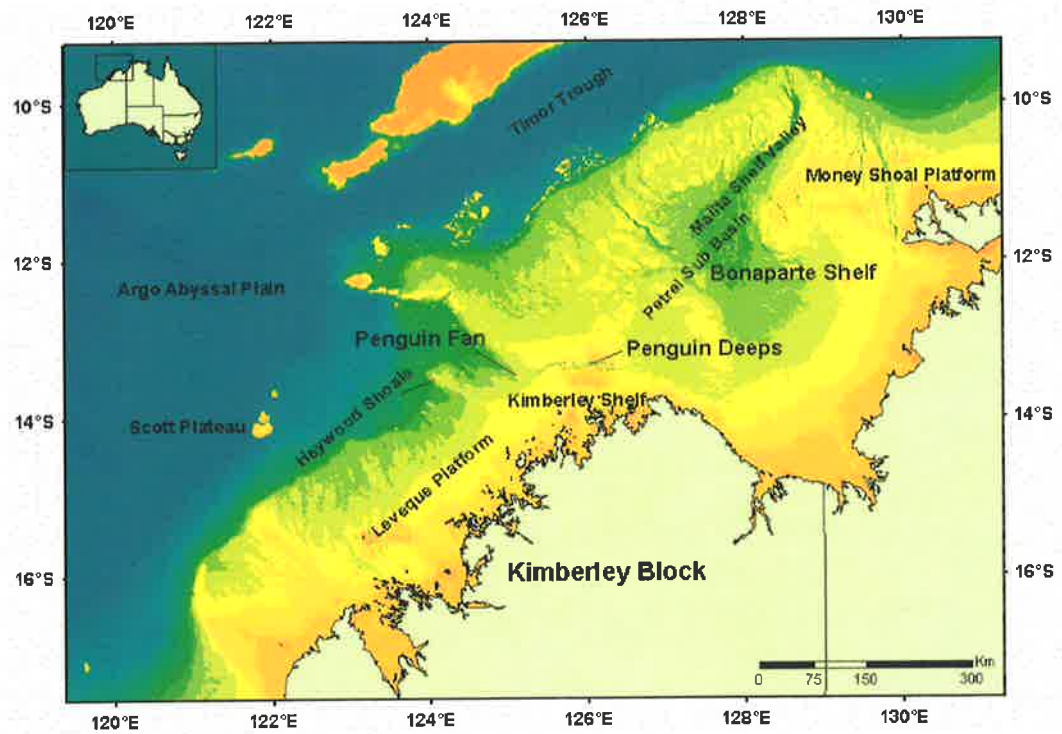


Figure 1.4 Present day bathymetry.

1.3 Thesis aim

This thesis aims to provide a detailed description of seabed morphology, stratigraphy and surficial sediment distribution in the Kimberley Shelf-Penguin Deeps-Browse Sea-valley area, based upon modern digital bathymetry and the collection of seismic lines, core and seabed grab samples. This information is used to describe the distribution of sediment facies which occur throughout the area, and to infer the late Pleistocene and Holocene processes which have controlled the development of the shelf morphology and the sediment distribution upon it. These new data throw new light on the origin of the terraced shelf and upper slope of the Sahul Shelf.

The purpose of this thesis is to;

1. Acquire, describe and interpret a series of surface samples and marine sediment cores using physical analysis, geochemistry and dating methods.
2. Identify the distribution of surficial sediments by chemical analyses and physical attributes.
3. Identify the origin of relict and palimpsest facies.
4. Interpret the evolution of the Penguin Deeps sediment transport and depositional system during the Quaternary.

1.4 Bathymetric nomenclature

The zig-zag western edge of the Bonaparte Shelf platform, and an outer shelf canyon termed the Penguin Deep which connects to the Browse Sea-valley offshore (Figure 1.1) in the study area, are both controlled by inherited relief from basement faulting. The importance of the Sahul Shelf, which is part of the wider Northwest Shelf, as a petroleum-producing province has resulted in a voluminous recent literature on the geology of the deep basins along the northwest Australian margin (e.g. Purcell, and Purcell 1988). One result of this has been the development of a confusing and sometimes overlapping nomenclature between seafloor and deep-seated basinal features. The nomenclature used here is applied to *seafloor features* along the margin, and is taken largely from the earlier papers by Fairbridge (1953), van Andel (1965) and Veevers and van Andel (1967).

Whilst adhering to "consensus" names for the major bathymetric features throughout the text, priority has been given to established named bathymetric or geographic features. There has also been occasion to appoint several new terms for bathymetric features discussed in the text.

New terms and their locations (Figure 1.1)

- ‘Kimberley Shelf’ (new term), derived from the adjacent onshore block, for the narrower shelf area north of the area colloquially termed Yampi Shelf, south of Penguin Deep and offshore from Admiralty Gulf-Collier Bay.
- ‘Browse Sea-valley’ (new term) for the depression on the northern edge of the Browse Basin and Greater Londonderry Rise that includes both the West Londonderry and East Londonderry rises.

1.5 Large-scale bathymetric features.

- *Sahul Shelf*

The *Sahul Shelf* (Fairbridge 1953), or platform, located north of the westerly-running sigmoid line of the Penguin Deeps-Greater Londonderry Rise (Figure 1.3). encompassing the bioherms and topographical highs of the Bonaparte Shelf towards the shelf edge break.

- *Kimberley Shelf*

To the south and southwest of the Penguin Deeps, this relatively narrow (~50 km-wide) shelf exhibits a deeply indented and cliffed coastline and stretches between Cape Leveque and Cape Londonderry.

- *Browse Sea-Valley*

- *Greater Londonderry Rise.*

At the northwestern end of this shelf, the Heyward Shoals shelf projects oceanwards, and delimits the *Browse Sea-Valley* between it and the *Greater Londonderry Rise* which runs from the western terminus of the Penguin Deeps on a north west trend out to Ashmore Reef .

- *Bonaparte Shelf*

- *Joseph Bonaparte Gulf*

To the northeast of the Greater Londonderry Rise, the *Bonaparte Shelf* comprises a 600 km-long by 400 km-wide platform which encompasses the large *Joseph Bonaparte Gulf* at its southeastern corner. The Bonaparte Shelf has a low regional slope towards the northwest, on top of which are developed two types of bathymetric relief have developed.

- *Bonaparte Depression*

At a greater scale, the offshore *Sahul Shelf* and *Greater Londonderry Rises* define an a region of shallower bathymetry, at the centre of which lies the *Bonaparte Depression*.

- *Melita Shelf Valley*

This Bonaparte Depression reaches depths of 132 m, and is connected to the open ocean through the *Melita Shelf Valley* (axial depths up to -200 m) to the north, and a number of other smaller, less incised valleys to the northwest.

1.6 Shelf terraces.

At slightly smaller bathymetric scale, "the most striking feature of the (Bonaparte) shelf topography is the widespread occurrence of flat, subhorizontal surfaces, separated by short, steeper slopes" (van Andel, and Veevers, 1965, p. 696), which were described by Fairbridge (1953) as "cuestas". The riser-separated terraces have low gradients of 5:1000 and occur consistently at depths of about 5-10, 20-30, 45-55, 64, 73, and 91 m,. Many of them can be correlated regionally. Veevers and van Andel (Figure 3; 1967) traced their surfaces III (50-70 m) and IV (90-110 m) throughout the Bonaparte Shelf, though mapping them at a significant range of depths. Adjacent terrace surfaces converge towards the rises, and diverge towards the outer shelf and the Bonaparte Depression.

Inner, middle and outer shelf. (Fairbridge 1953) subdivided the Bonaparte Shelf into inner and outer shelf portions, separated across the 10-15 m high scarp that commonly occurs in the vicinity of the 55-60 fathom (~100-110 m) isobaths, which he interpreted as marking the lowstand shoreline at the last glacial maximum (MIS 2). The shelf-slope break, at 300 fathoms (~500 m) depth was

taken at a regional increase in seabed slope at 300 fathoms (~500 m) depth. For the purposes of this thesis, three subdivisions of the Kimberley Shelf are recognised, namely an *inner shelf* between the shoreline and the 50 m isobath (corresponding approximately to the offshore edge of the terrigenous Inner Shelf Prism (ISP)), a *middle shelf* between 50 and 105 m depth (a current-swept, sediment-starved plain), and an *outer shelf* between 105 and 150 m depth (corresponding to areas of deeper terrace).

Though Fairbridge (1953, p.8) states that terraced morphology is restricted to his inner shelf, on the Kimberley Shelf sector terraces underlie the inner, middle and outer shelf, and also continue down the slope to a depth of at least 230 m. The irregular surface of the shelf and upper slope terraces, due to the occurrence of both encrustation (including reef formation) and erosion since their formation, makes it impossible to attribute them to one precise depth, especially as the depths of individual shelf terraces may differ in level by up to 15 m between their shoreward and seaward edges (e.g. van Andel and Veevers, 1965). The Kimberley Shelf terraces are referred to, for descriptive purposes, the in terms of the estimated depths of their seaward edges, the most widespread ones being the 30 m-, 45 m-, 60 m-, 75 m-, 95 m-, 112 m-, 165 m- and 185 m-terraces (as shown in cross section and discussed in chapter 5). Thus defined, the depths of all Kimberley Shelf terraces down to and including the 112 m-terrace fall within the general depth spans of terraces recognised by earlier workers on the Bonaparte Shelf sector of the Sahul Shelf (Fairbridge 1953; Carrigy, and Fairbridge 1954; van Andel and Veevers, 1967) and are discussed in detail in Chapter 5.

Chapter 2. Mapping

2.1.1 Previous Maritime Mapping History

The Northwest Shelf (NW Shelf) of Australia (Figure 1.1) is an area steeped in an unusual maritime history. The history of European mapping of Australia has been referred to as having ‘peculiarities that cannot be found in any other series of maps’ in the world (Tooley 1961). This land mass was ‘sensed’ prior to its European discovery, and postulated by Pre-Christian cosmographers map makers (Tooley 1961), to ‘counter balance’ the known northern landmasses.

The Australia continent was first authenticated in map form by both the Dutch and Spanish in 1605. There are also indistinct assertions of a previous Portuguese visit (Tooley 1975). Some weight has been given to the map produced by Paolo Toscanelli (1397-1482), an Italian physician, cosmographer, astronomer, mathematician and geographer. He acted on Marco Polo’s information to produce the 1474 ‘Toscanelli Map’, the map used for the famous Columbus-led discoveries.

The Sahul Shoals on the northern shelf edge of northwest Australia (Figure 1.3) are clearly sited on the Alphen map printed in 1660 and Coronelli’s 1696 map of the ‘top end’ of Australia (Figure 2.1). Coronelli’s map states that Australia, named on the map as ‘terra di Concordia’, was recorded in 1618 (Appendix 2.1), one hundred and fifty two years before Captain Cook lay claim to Australia. The Alphen map (1660) incorporates the information from the previous journeys of discovery to the western Australian coastline, including Leeuwin (1621), P. Nuyts (1627) and F. de Wit (1628).



Figure 2.1 Coronelli's 1696 map of the 'Top End' Australia (see appendix 2.1 for text translation) from Tooley 1961. This indicates that the mapping of Australia has been a progressive processes made by navigators and mappers from a range of European countries.

The maps by DuVal (1665) Kenlen (1680) and Loots (1685) in Tooley (1975) all show small islands within a reef directly to the south of Timor (Figure 2.2), which probably represent the group of islands within Ashmore Reef. Additionally, numerous reefs and islands off the northern Western Australian coast are charted. The close proximity to Indonesia probably resulted in European explorers on several journeys making contact with the north Australian mainland whilst on route to Jakarta (then Batavia), thereby increasing the mapping of Australia.

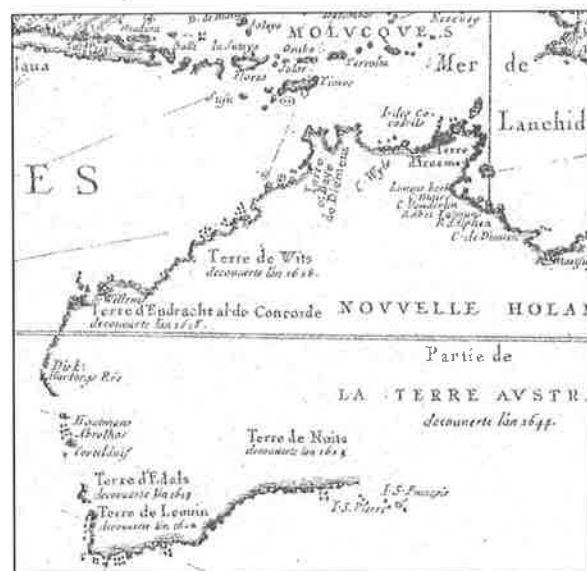


Figure 2.2 From the map by Duval (1665) in Tooley (1975) indicates increased mapping effort to the north of Australia highlighting shoals and reefs.

Nevertheless, it was Abel Tasman (1644) who was responsible for charting much of the western and northern Australian coastline from south of the Northwest Cape across to Cape York. Tasman established that Eendracht Land (Western Australia) and Carpentaria (Queensland) were a part of a single land mass that was separate from New Guinea and the East Indies (Tooley 1961). This was important for European maritime charting, as he created the nautical foundation for the explorations of James Cook.

Indonesian fishers have been sailing to the offshore Australian reefs (e.g. Ashmore Reef) since the eighteenth century (Fox, and Barlow 1996; Fox 1998), (Stacey 1998; Stacey 2001) along with the American guano miners and whalers (Marsden 2002).

English privateer William Dampier, on the *Cygnets*, mapped the west Australian coast in 1688 and again, two years later, on the HMS *Roebuck*. The French explorer, Allouarn, skirted the northern coast in 1772, and Captain Peter Heywood on the HMS *Vulcan*, mapped more of the Kimberley coast in 1801.

In Napoleonic times, Nicholas Baudin, mapped the southern coasts of Australia, travelled north towards Timor, named Geographe Bay and explored Shark Bay on the Western Australian coast. He also charted the coastline across to the Gulf of Carpentaria, including a survey in 1803 on the *Casuarina*.

Rear Admiral King carefully mapped significant parts of the northern Australian coastline. In 1817, he took command of the HMS *Mermaid*, to explore the north-west coast, up to and including, Arnhem Land. His three other voyages during the period 1818 - 1822 were followed by Captain Wickham and Commander Stokes,

in HMS Beagle from 1837 - 1843 (Hordern 1992; 1997) who extended Kings work. It is from the naturalist studies of the Timor Sea and surrounds by HMS Penguin in 1892 (MacLay 1998), that the Penguin Deeps, acquired its name. Many of the charts from these surveys were in use up until 1945 (Hordern 1997). Ongoing improvements have been made regularly by the Royal Australian Navy, Hydrographic Service, since 1920.

2.1.2 Marine geological mapping

The marine sediments and offshore bathymetry of the wider study region have been investigated by a limited series of surveys. Teichert, and Fairbridge (1948) looked at the coral reefs of the Sahul region. Their study was followed by structural appraisals by Carrigy, and Fairbridge (1954) and Harris et al. (1994). The van Andel and Veevers study (1967), located just to the north of the study area, was the first regional marine geological survey and remains the most comprehensive sediment study to date. The study contains a detailed appraisal of the surficial sediments but lacks geophysical or stratigraphic data. (Jones 1968; Jones 1970; Jones 1973) undertook a sedimentological and morphological survey to the south of the study region and likewise offers no stratigraphic interpretation of the underlying sediments. Jones (1968), importantly, recognised that there is a widely observed 'notch' at ~120 m water depth, which today, is thought by many, to represent sea level (SL) at the last glacial maximum (LGM). Veevers (1969) reviewed this work with the new information from exploration wells being drilled in the area, particularly the Ashmore well #1 and associated seismic surveys. He interpreted palaeogeographies of the Timor Sea region highlighting the interplay of sea level change from the Permian to the Holocene. Veevers (1970) commented on the shallow stratigraphy and continental margin structure within the gross depositional and structural patterns of the Sahul Shelf.

Geoscience Australia (previously known as the Bureau of Mineral Resources and the Australian Geological Survey Organisation) has had multiple geological surveys over the NW Shelf from 1962 to 2002, including one targeted for this study, Survey 225. Along with industry surveys, a total of 93 marine surveys

have been undertaken in the region bounded by 12° – 14° South 123° - 128° East, between 1962 - 2002. The shallow regional stratigraphy and thick Palaeozoic sequences were documented by (Veevers 1982), while the stratigraphy and structure of the southern Sahul was detailed by (Labutis 1994). Cambridge Gulf Diamonds and Western Mining Corporation (1997) both evaluated the nearshore sediments for diamonds in Commonwealth, Western Australian and Northern Territory state waters in unpublished reports. (Clarke and Ringis 2000; Clarke et al. 2001) described the late Quaternary offshore stratigraphy, then further analysed the post-glacial transgression and highstand marine and marginal marine sediments of the southwest Joseph Bonaparte Gulf. To the northwest of the study region Glenn (1997, 2002, 2004) O'Brien et al. (2002) and Glenn and Collins (2004) have described reef development and hydrological and sedimentological data respectively at Ashmore Reef.

2.1.3 Onshore geological mapping

Previous onshore mapping begins with regional survey work by (Hardman 1885) in search of economic minerals. The east Kimberley, the Ord and Bonaparte Basins and ranges were explored by Matheson and Teichert (1948). Guppy, and OEpiik (1950) Guppy (1955); Guppy et al. (1958) discovered Ordovician rocks in the Kimberley, and investigated the sand dune areas of the north-west and the geology of the Fitzroy Basin respectively. Noakes (1951); Noakes et al. (1952) provided a stratigraphic summary of the onshore Bonaparte Basin. (Traves 1955) assessed the drainage basins of the Ord and Victoria Rivers and their geological hydrology and geological history, naming several units of the onshore Bonaparte Basin and appraising their economic promise. Harms (1959) considered the

geological history of the Kimberley Basin, Roberts and Veevers (1929, 1958; Roberts and Veevers 1971; Veevers, and Roberts 1968) the Upper Palaeozoic rocks in the Bonaparte Gulf Basin and Roberts and Veevers (1929, 1958) and Veevers (1973) Mory and Beere (1988) comprehensively assessed the geological history of the Ord and Bonaparte onshore Basins, including the palaeo-geography, basin evolution and economic geology. Summaries of specific onshore basins include: the Bonaparte Basin (Mory 1990a), the Ord Basin (Mory 1990b) and the Kimberley Basin (Griffin, and Grey 1990). Lees, et al. (1990); Lees (1992a); Lees (1992b) assessed the terrigenous - carbonate sediment transition of the Joseph Bonaparte Gulf, recent terrigenous sedimentation and chenier development and ages of a chenier sequence on the Victoria Delta, respectively. (Wasson 1994) interpreted the decadal variation in sediment yield and Wasson et al. (1996) ascertained the erosion and transport rates for the Ord River. Wasson et al. (2002) evaluated the controls on sedimentation in Lake Argyle, using spatial traces, which included mineral particle magnetics, and strontium and neodymium isotopic ratios. The study by Wasson et al. (2002) provided insights into the effectiveness of different types of erosion and sediment provenance and found that 96% of the sediment entering the lake came from 10% of the catchment area.

2.1.4 Industrial Mapping

Hydrocarbon exploration has been undertaken on the NW Shelf of Australia since the 1960's, and high resolution seismic and bio-stratigraphy analysis of the sub-surface units have assisted in finding oil and gas reservoirs and has led to its recognition as a world class hydrocarbon province (Figure 2.3). A valuable by-

product from the industry surveys is the quality bathymetric data which assists in sea floor mapping and bio-regionalisation projects.

The first petroleum well (Ashmore #1) was drilled to a depth of 3 914.5m by British Oxygen Company (BOC) in 1968 (BOC, and Craig 1968), and 23 wells have been drilled in the area under study (Figure 2.3). Despite almost 80 industry surveys in the region, the available industry seismic is unsuitable for this study because it is focused on deep stratigraphy. There are currently no producing wells in the study area. Unfortunately no high frequency or sedimentological survey is recorded in the well reports. Thus there was no surficial sedimentological work in the Penguin Deeps or Penguin Fan area.

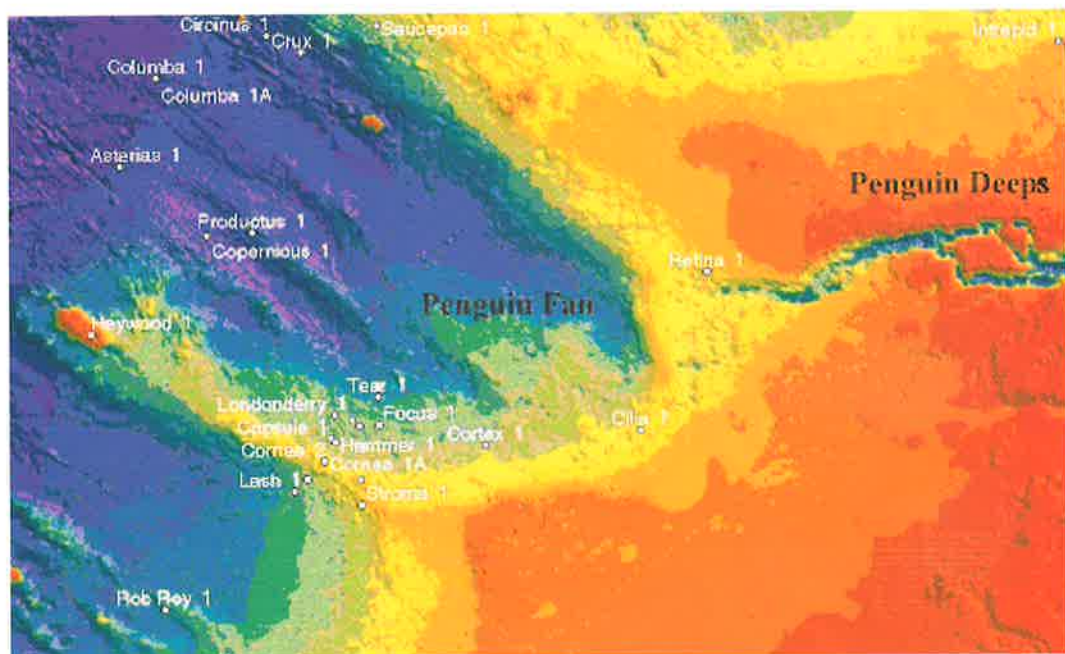


Figure 2.3 Regional hydrocarbon exploration wells (none are production wells)

2.1.5 Mapping regional hydrocarbon seeps

Naturally-occurring hydrocarbon seeps are common in the area (O'Brien et al. 2000, 2001 2002 a, b, c, 2003) and potentially make significant inputs into the marine food webs (Glenn 2000). The benthic communities and many of the coral reefs are spatially and may be causally related to such seeps (O'Brien et al. 2002). The hydrocarbons potentially provide a primary food source or substrate, allowing pioneer organisms to establish environments suitable for reef initiation and the growth of colonial corals.

2.1.6 Mapping the regional bathymetry

Geoscience Australia has been collecting bathymetric data from the NW Shelf since 1963 (Petkovic and Buchanan 2002). The database includes surveys and contributions from other institutions, such as oil exploration companies and the National Geophysical Data Centre (Appendix 2.2). The database therefore contains data from a variety of systems, with various levels of accuracy. Geoscience Australia holds a database of swath bathymetry in deep water, laser airborne depth sounder (LADS) data and points digitised from Australian Hydrographic Service charts in addition to the ship-track data. These data, together with predicted bathymetry from satellite altimetry, have been brought together into a single database, which has been processed to create the grids and images used throughout this study.

2.2 Regional Structural Geology

2.2.1 Margin Scale Basins

The underlying geology and physiography of the Timor Sea region is dominated by two margin-scale basin systems, the Bonaparte and Browse basins (Figure 2.4). These margin-scale basins or compartments, are separated by a sharp, north-west trending Proterozoic basement feature (O'Brien et al. 1993; O'Brien 1993) which has strongly influenced basin architecture from at least the Mesozoic to the present day.

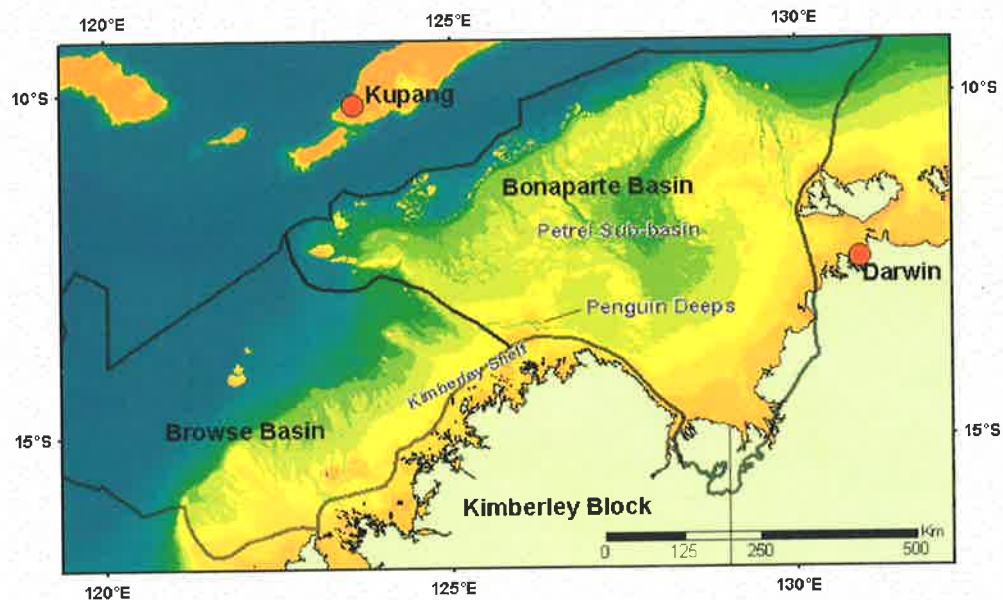


Figure 2.4 The Bathymetric expression of the NW Shelf Australia showing the principal Bonaparte and Browse Basins.

The structural development in the region commenced in the Siluro-Ordovician, with the deposition of evaporitic sediments. Subsequent rifting on a broadly north-east extensional azimuth (Gunn 1988) in the Late Devonian to Early Carboniferous was focused in the Petrel Sub-basin (Figure 2.4), which formed a north-west trending basin system which extended from the Joseph Bonaparte Gulf out under much of the present day Bonaparte Basin.

This north-west trending rift system was subsequently over-printed by two generally north-east trending rift systems. The first developed during the Early Permian extension, whereas the latter formed during the Middle to Late Jurassic rifting, that led to the development of the Mesozoic rift elements (Baxter et al. 1997; Baxter et al. 1998) and adjacent abyssal plains which dominate the region to the present day (O'Brien 1993).

The Bonaparte and Browse Basins have quite different rift and reactivation histories, as well as Late Tertiary physiography. The Bonaparte Basin developed as a relatively wide (low topographical gradient) margin component and experienced relative gentle post-rift subsidence. As a result, the Early Cretaceous sealing facies through this region are relatively thin, typically less than 100m thick (O'Brien 1993). In contrast, the Browse Basin subsided rapidly in the Early Cretaceous, and as a consequence, the Early Cretaceous shales which provide the seals to the hydrocarbon accumulations in this region are thick, often exceeding 500 m in thickness (O'Brien et al 1999).

In the Late Tertiary, the progressive convergence and then collision of the Australian and Eurasian plates dramatically modified the physiography of the region (Hillis et al. 1997; O'Brien in press). Outboard of the Bonaparte Basin, it appears that a marginal plateau system, not unlike the present day Exmouth Plateau, was rapidly uplifted in the Pliocene. The uplifted region constitutes part of what is now Timor Island, with the attendant formation of an inboard foreland basin or foredeep (the Timor Trough). This Pliocene collision produced increased subsidence rates across the Bonaparte Shelf, but in some areas, very rapid

subsidence (over 500m/Ma), produced deep water (>700 – 800m) troughs (such as the Cartier Trough) which contain thick (>500m) Pliocene deposits, surrounded by slower subsiding rims. It is around these rims that many of the carbonate banks and shoals in the region have developed (see Figure 1.3). In contrast to the Bonaparte Basin, the Browse Basin was much less affected by Neogene tectonism (O'Brien 1993).

These Neogene tectonic events, most of which have occurred in the last 5 million years in the Bonaparte Basin area, dramatically modified the regional oceanography. In particular, plate convergence and associated uplift resulted in the formation of a narrow and deep topographic depression, the Timor Trough. Moreover, the fault reactivation associated with this collision caused extensive leakage of hydrocarbon accumulations in the area (O'Brien and Woods 1995; O'Brien and Fellows 1996; O'Brien et al 1999). It appears that the combination of this rapid, focused leakage of hydrocarbons up Pliocene fault systems and increasing Pliocene subsidence rates played key, and perhaps causal roles in the development of the majority of the carbonate reefs and banks in the region (O'Brien et al 2003) (Figure 2.5).

2.2.2 Carbonate Reef Development

A three-phase bioherm development model for many of the carbonate reefs and banks in the Bonaparte shelf region has been presented by O'Brien et al. (2002). The model proposes that many of the basin edge reefs and build-ups in the region formed via a relatively simple, sequential process. First, an active petroleum system with charged traps and active hydrocarbon migration fairways existed (Figure 2.6a). Next, collision-related faulting in the Neogene (probably early

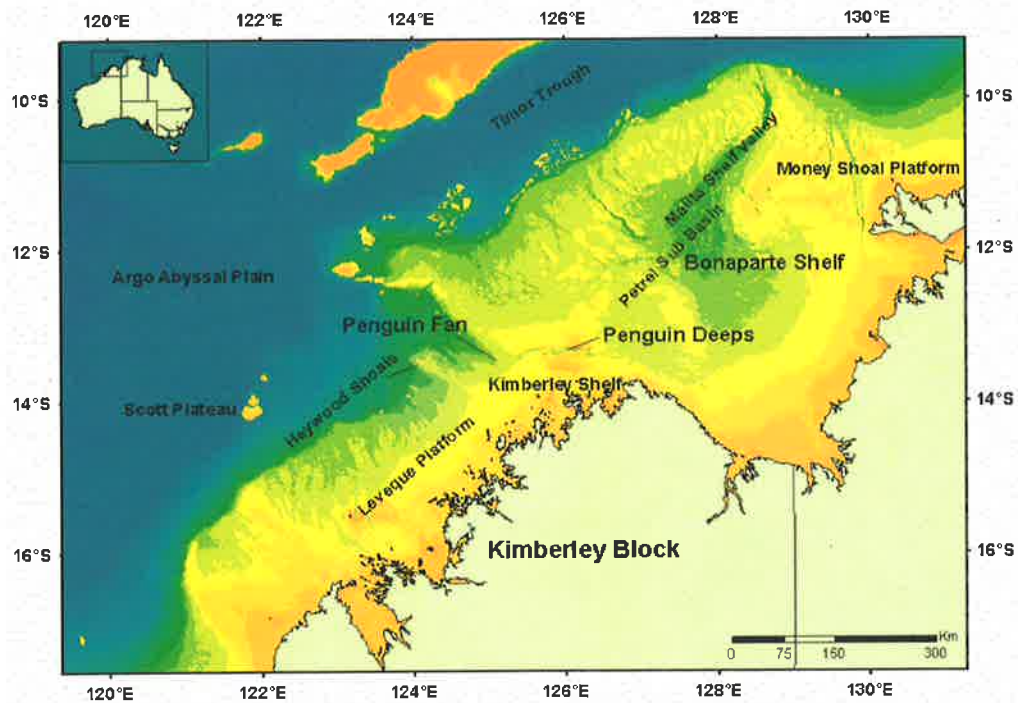


Figure 2.5 The Bathymetric expression showing the major features of the NW Shelf Australia.

Pliocene) induced hydrocarbon seepage above charged hydrocarbon accumulations or migration fairways. This resulted in the development of small, localised sea-floor bacterial and (chemo-synthetic) biological carbonate communities which established themselves, potentially using the hydrocarbons as a food source (O'Brien 2002). These communities eventually formed topographically positive features which subsequently became preferentially colonised by an assortment of reef and bank building biota (Figure 2.6b).

Finally, reef and bioherm communities, which are not seep-reliant, maintained their position within the photic zone by keeping pace with the rapid Pliocene subsidence. Subsidence rates around the banks of 100 – 200 m/Ma were common, although in some areas subsidence rates exceeded 500m/Ma.

Subsidence rates in the Timor Trough were much higher. Rates determined by

examination of data from the DSDP hole 262 (O'Brien et al. in press) indicated that as much as 2500m of subsidence may have occurred in as little as 1 million years in the Pliocene. This resulted in the development of a range of bioherm expressions which were surrounded by much deeper water (Figure 2.6c).

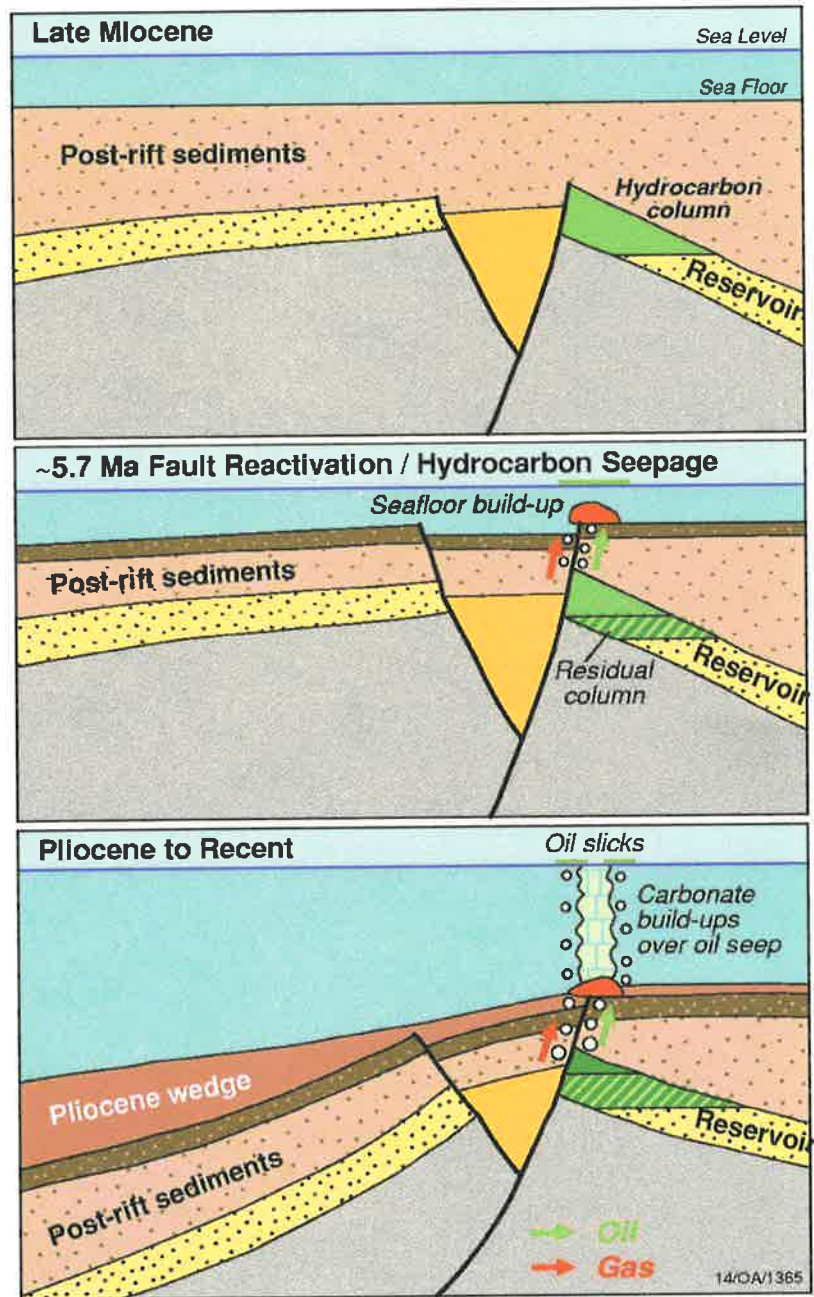


Figure 2.6 a,b,c. The model for the sequential development process of Bonaparte Shelf bioherms (O'Brien and Glenn, 2002). The pioneer biota inhabit or form a suitable substrate for a succession of photosynthetic reliant reef builders.

Additionally, plate collision during the Pliocene led to the development of the Timor Trough, as well as significantly increased regional subsidence rates, previously mentioned. This trough has since become a major conduit for the Pacific Ocean waters flowing into the Indian Ocean.

O'Brien et al. (2002) and O'Brien (2004) provided seismic evidence that the banks and reefs of the Bonaparte shelf were absent in the mid-Miocene, and developed in the early Pliocene. Many of these, including the Sahul Shoals (Figure 1.2), have since kept up with sea level rise and exhibit strong modern carbonate productivity. There is a high degree of diversity of carbonate-fixing taxa both within, and between, the banks (Heyward et al. 1997), which are major contributors to the regional sediment budget. With few exceptions, the surface of these flat-topped banks tend to be algal (predominantly Halimeda) - and sponge-dominated in the north, whereas further south, Ashmore, Cartier, and Hibernia reefs are coral-dominated (Glenn 1997). The cause for the difference between southern coral-dominated and northern algal-dominated substrates, may be related to water quality, such as water temperature and salinity variation due to the Indonesian Throughflow, Indian Ocean upwelling or even local inputs including hydrocarbon seeps or a physical control from cyclone activity or internal waves (pers. comm. A. Heyward 2004).

A physical control, such as cyclone damage of the benthic biota, may allow the faster growing algal species, such as Halimeda with an average growth rate of $3.0 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ (Milliman 1993) to out grow the slower, more structurally robust, colonial corals which have a bulk growth rate of $1.0 \text{ } 1.2 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$

(Smith 1983). Halimeda is capable of re-establishing itself rapidly after the substrate is 'mowed' by cyclone induced waves. The fast growing nature of this calcareous alga and the evidence of high energy storm events in the gravity cores (Chapter 4) suggests that Halimeda may be one of the first in a succession of biota re-establishing itself after a catastrophic event.

The apparently long-lived differences in topographic gradient which have been present between the Bonaparte and Browse Basin transition zone means that it has been a major entry point for terrigenous sediments through several channels (Figure 2.7) since at least the Cretaceous (O'Brien et al. 1999). This is particularly evident in the distribution of low-stand, terrigenous fans. Several of these drainage channels have allowed the transfer of fluvial and ITF water between the Bonaparte Basin and the Indian Ocean at different times. Such channels provide primary entry points into the rift system for terrigenous sediment, particularly during low stands, as they cut through the substrate and deposit their bed load in deeper water. Today, one such input corridor is expressed as a major east west trending channel system known as 'The Penguin Deeps' (Figure 2.7).

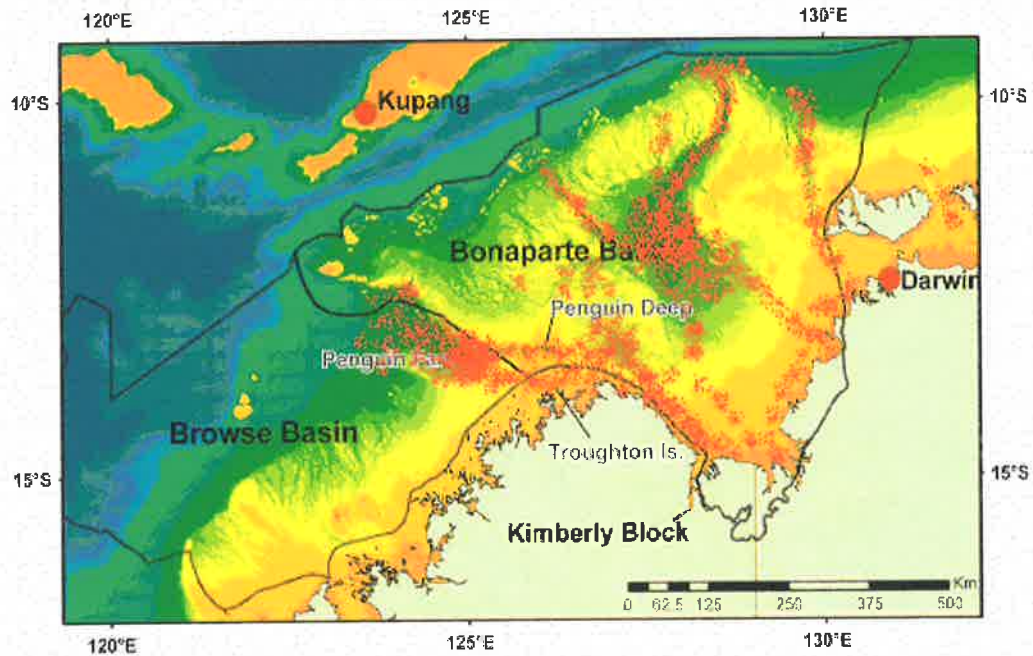


Figure 2.7 Depo-centres and sediment pathways at times of lower SL

The wider shelf itself is generally viewed as an erosional surface largely devoid of Holocene sediments, i.e. it is a sediment bypass zone (Harris 1994), whereas the northern offshore edge of the shelf hosts a key carbonate factory with a range of genetically diverse bioherms having high biodiversity (Figure 1.3).

2.2.3 Tectonic setting: rates of subsidence

The original rifting of the Sahul Shelf part of the northwest Australian continental margin dates back to the creation of the eastern boundary of the Indian Ocean in the Triassic-Jurassic (Veevers et al. 1991). The stretched edge of Australian continental crust tapers in a northeasterly direction, beneath the Sahul shelf-edge and slope. At the mouth of the Penguin Deep, the Bonaparte and Kimberly Shelf edges are displaced by about 200 km from each other across the Londonderry Rise which represents the location of a deep-seated basement fault or accommodation zone (O'Brien et al., 1993). Paired east-west linear features, possibly also fault-controlled, occur at the east and west ends of the Londonderry

Rise as the Penguin Deeps and Ashmore Scarp, respectively. Thus the seaward, zig-zag edge of the peri-continental Kimberley-Bonaparte platform was shaped by tectonic forces during the Mesozoic phase of rifting of the northwest Australian margin (Fairbridge 1953). Mesozoic-Cenozoic subsidence, caused by thermal cooling and sediment loading, followed the rifting phase and created the accommodation space for deposition of the sedimentary successions of the Browse and Bonaparte Basins. Simple models of rifted continental margins (e.g. McKenzie 1978) predict a subsidence rate of ~ 1 cm/ky or less should be obtained for the edge of a rifted continent some 100 My after the rift event.

Since Gregory (1913) first described the ria-like morphology of the western side of the Kimberley Block (and therefore the shoreline to the Kimberly Shelf), it has been understood that this area must have undergone strong and recent subsidence. Further, the presence throughout the Sahul Platform of shelf and slope terraces down to depths of several hundred metres has been interpreted by all earlier workers as requiring significant Late Cenozoic subsidence (e.g. Carrigy and Fairbridge 1954; Fairbridge 1953; Jongsma 1970). Geomorphic and bathymetric features such as those described from the Kimberley coast and Sahul Platform do not occur on mature continental margins elsewhere which are now subsiding at slow rates of < 1 cm/ky, and it is therefore clear that the modern Sahul margin is being influenced by some other tectonic factor. That factor is the development of strong Pliocene downwarping within the Timor Trough (O'Brien et al. 1999), which separates the Sahul platform from the Indonesian volcanic arcs, and which is associated with the development (since the Late Miocene) of the Cartier Trough beneath the outer part of the Sahul Platform (Kennard 1999).

It has been understood since the 1970s that for passive margins, worldwide, the edge of the continental shelf corresponds broadly to the stretched edge of the pre-rift continent. The depth of a particular shelf edge is therefore controlled by the interaction of (i) the rate of thermal subsidence, which relates to the amount of extension in the underlying lithosphere and the time since rifting (McKenzie 1978); and (ii) any processes of erosion (e.g. scarp retreat at lowstand; ocean current erosion at highstand) or deposition (e.g. pro-delta progradation at lowstand; coral reef growth at highstand) that may modify the level of the shelf edge. In this regard, the rifted edge of the Sahul Shelf lies at ~80-100 m depth, which is similar to that of the Great Barrier Reef province (Maxwell 1973). The Sahul Shelf is unusual, however, in that conspicuous shallower- and deeper-water terraces occur commonly on both sides of the main shelf edge, suggesting higher rates of subsidence than those that characterise undisturbed passive margins.

The submergent geomorphology of the coastal region is well known (see earlier discussion pg 16, 19) and analysis of the spacing of the descending flight of submerged terraces on the Kimberly Shelf, suggests a rate of subsidence of ~15 cm/ky. This estimate used throughout this thesis, compares well with the rates of subsidence between 10 and 30 cm/ky for the last several million years reported for the flanks of the northeast-oriented Vulcan Graben-Cartier Trough, a developing post-Miocene basin which lies under the northern wall of the Browse Sea-valley parallel to and just seawards of, the edge of the Kimberly Shelf, separating the offshore Ashmore block from the main Londonderry High (Kennard 1999).

Chapter 2.3 Oceanography

2.3.1 Regional Oceanography

To the north and northwest of Australia across the Indonesian archipelago (Figure 2.8) an unusual oceanographic occurrence takes place, it is the world's only tropical inter-ocean interface. Here the Indian and Pacific Oceans coalesce, the waters of the Western Pacific Warm Pool (WPWP) flow into the cooler, higher salinity Indian Ocean through the Indonesian archipelago at a rate of $\sim 10 - 15$ Sverdrups ($Sv = 10^6 \text{ m}^3/\text{s}$). This flow is termed the Indonesian Throughflow (ITF) and is part of the Global Conveyor Belt (Figure 2.8) or thermohaline circulation (Broecker 1991). Maximum flow occurs during July to September, and plays a significant role in the global heat budget, the fresh water balance (Molcard et al. 1994; Baptiste et al. 1997; Chong et al. 2000; Field et al. 2000; Vranes et al. 2002; Cane et al. 2003; Gordon et al. 2003) and associated climate regimes.

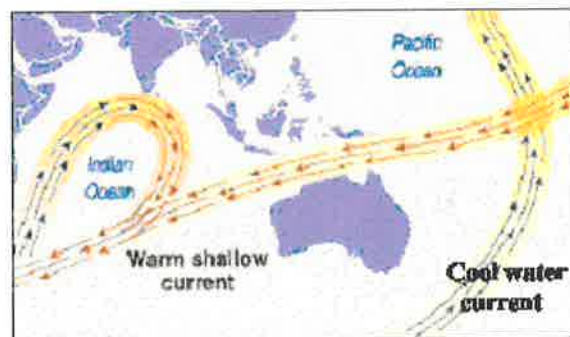


Figure 2.8 Regional perspective of the Global Conveyor Belt or Thermohaline Circulation (from Broecker 1991 in Climate Change 1995)

There is no other place on earth where such a large volume ($\sim 10 \text{ Sv.}$) of tropical water banks up and flows geostrophically from one ocean to another. Located at the northern edge of the Bonaparte shelf and at the confluence of the Pacific and Indian Oceans, the ITF is the conduit for the important low-latitude oceanic interface (Glenn 2004) (Figure 2.9).

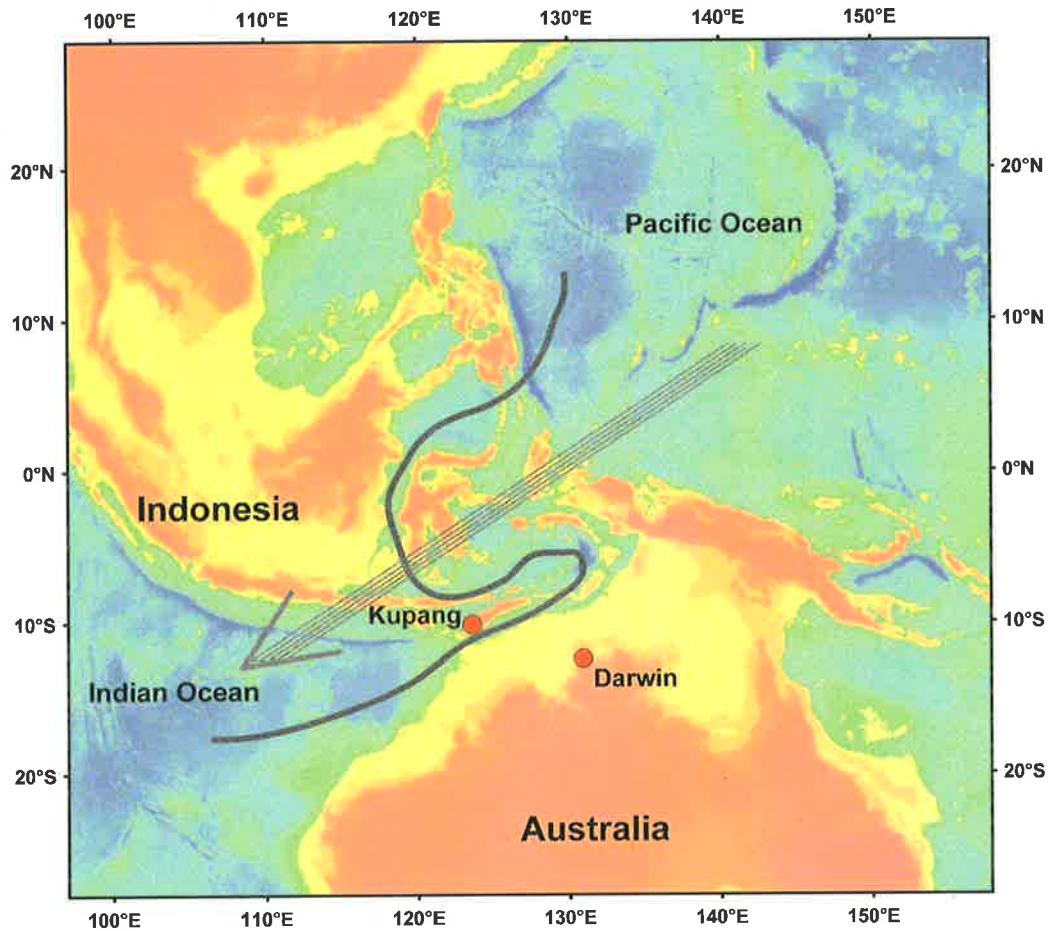


Figure 2.9 Regional oceanic setting and overall flow trend and track of the Indonesian Throughflow closest to the study region.

In fact, the high level of regional biodiversity is thought to be largely attributable to oceanographic inputs, diversity of habitat and geographical location, and possibly inputs from active regional hydrocarbon seeps (Glenn and O'Brien 2000, O'Brien et al. 2003, Glenn and Collins 2004).

Regional upper water column masses are warm (25.48°C to 30.2°C ; Glenn 2004), (Figures 2.10, 2.11), have low salinity ($\sim 34.2\text{‰}$ – 34.8‰ ; Wyrki 1958; 34.51‰ to 34.75‰ ; Glenn 2004) and are strongly mixed to $>50\text{m}$ depth.

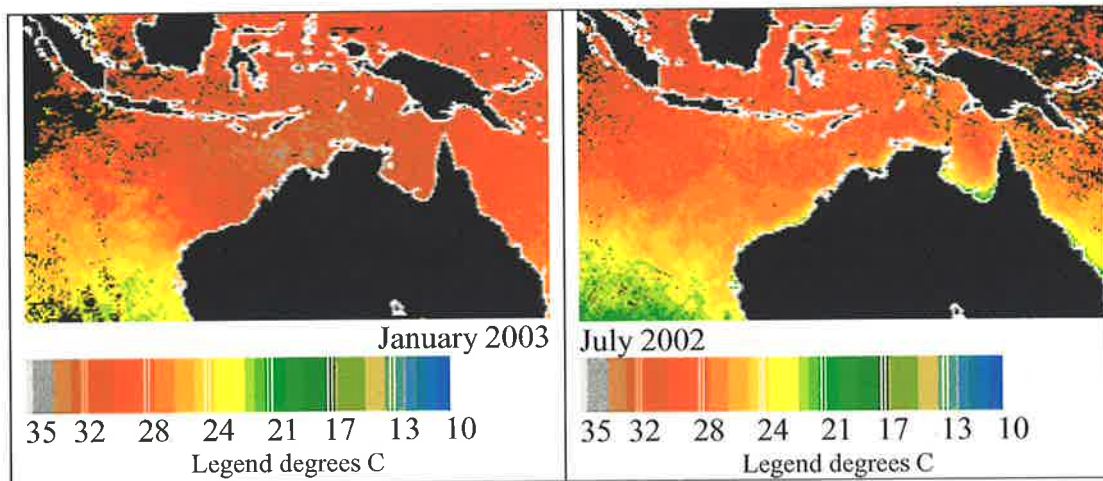


Figure 2.10 and 2.11. Regional Sea Surface Temperatures (Bureau of Meteorology 2003)

The energy transfer in the ITF varies with the ENSO phase, being higher during La Niña and lower during El Niño (Meyers 1996; Vranes et al. 2002). Both tidal and gravity waves contribute to oceanic mixing as the water mass travels through the archipelago. Mixing is encouraged further by sea floor rugosity (Schiller 2002) causing friction. There has been only limited annual study of the main gateways (Figure 2.12) and their flow rates (Chong et al. 2000) to ~500 m water depth, so that the exact amounts of heat and water transfer through the ITF are at best, approximately known (Table 2.1). Variability in the values occur due to the range of models being used in the calculations. Approximately half of the ITF water is channelled via the Timor Trough (Molcard et al. 1994), driven mainly by friction induced as the water flows via the Lombok and Ombai straits (pers. comm. S. Wiffels 2003) and by the pressure gradient between the two oceans (Jean-Baptiste et al. 1997). The rest of this flowing water mass enters the Indian Ocean through other gateways (Figure 2.13) including the Sumba and Savu straits (Chong et al. 2000). Others entrances do exist, depending on the sea level at the time (Figure 2.14, Appendix 2.3). A percentage of the water channelled through the Timor Trough will rise up onto the Australian continental shelf (Bonaparte

Shelf) but the greater part contributes to the south equatorial current (Wijffels et al. 2002) and a smaller percentage assists in the formation of the poleward flowing Leeuwin Current.

Researcher	Rate of Flow	Error margin
Fieux et al. 1994	18.6 Sv	± 7
Godfrey and Masumoto 1996	10.5 Sv	
Bray et al. 1997	5-10 Sv	± 5
Schiller et al. 1998	16Sv	
Gordon / MacLean 1999	12 Sv	
Chong et al. 1999	10-15 Sv	
Hautala et al. 2000	8.4 Sv	± 3.4
Lebedev / Yaremchuk 2000	11.5 Sv	
Creswell et al. 2000	7 Sv	
Wijffels et al. 2002	8.4 Sv	± 3.4
Gordon et al. 2003	10 Sv	

Table 2.1 Some published Indonesian Throughflow values

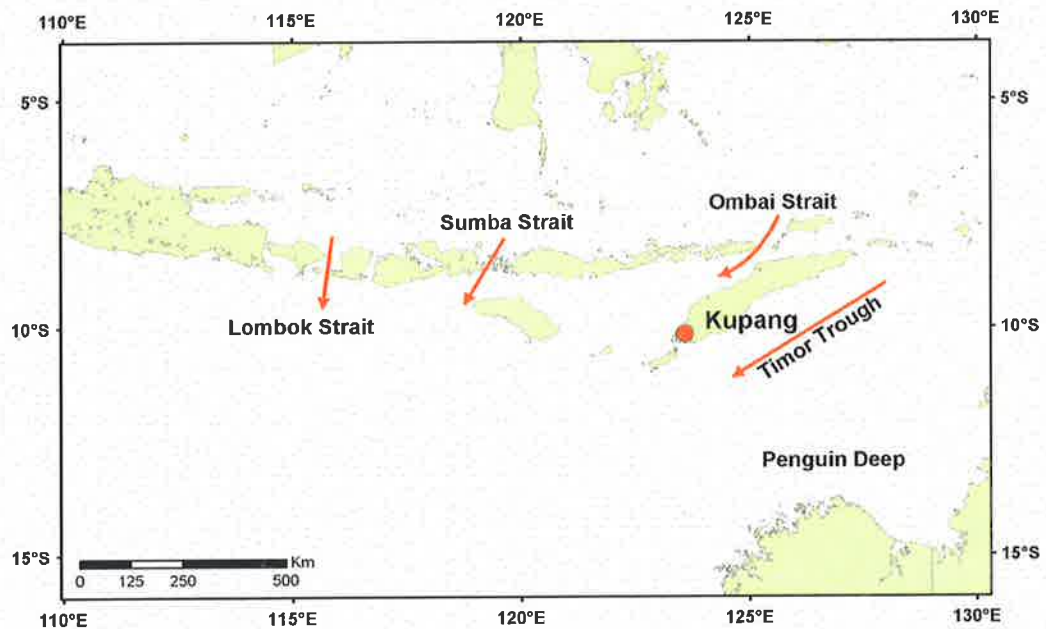


Figure 2.12 The main Indonesian Throughflow gateways

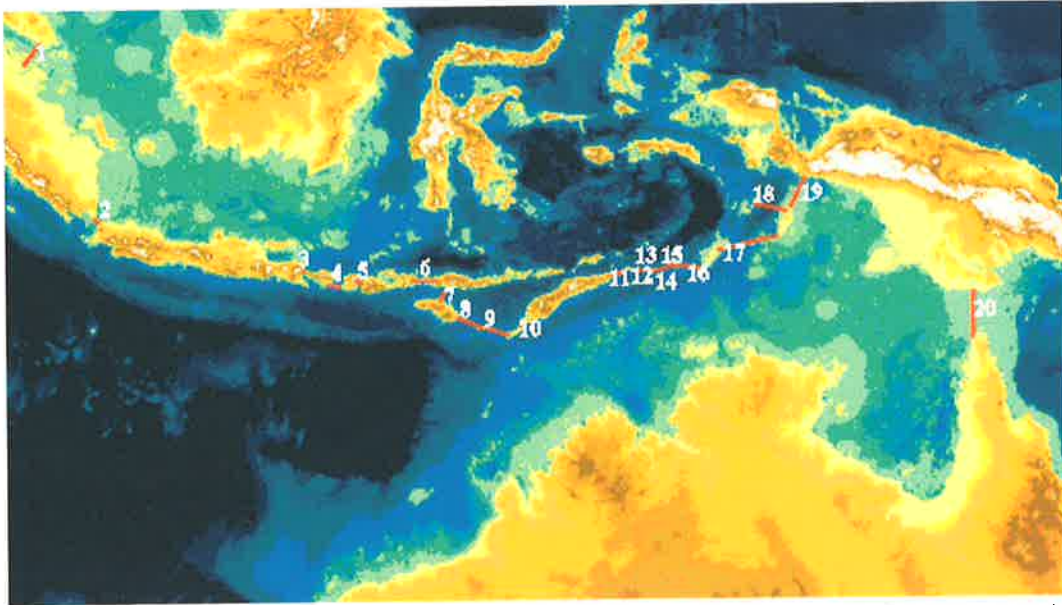


Figure 2.13 The Indonesian Throughflow Gateways. Profiles generated for this study in appendix 2.3.



Figure 2.14 The main conduit close to the study region between the islands of Sawu and Roti. The red line indicates the sea level at the Last Glacial Maximum.

The Leeuwin Current is the only poleward flowing, continental shelf, western boundary current. Driven by a steric height gradient, it is unlike other boundary currents, in that it flows into the prevailing winds (Church et al. 1989). Holloway (1995) terms it a low salinity ($35.2 - 35 \text{ ‰}$), warm current. It carries warm water

and associated biota down and around the west and southern coasts of Australia (Pattiaratchi et al. 1991).

Values for the southerly flow of the Leeuwin Current range from 4 – 7 Sv. The times may display reciprocal flow reversals in the north (Holloway 1995). The maritime significance is closely linked with changes in sea level, as this current it is strongly associated with the continental shelf. Importantly, this current provides a mechanism for pelagic and benthic biota gene flow, and thus it has had important implications for species occurrences and the reproductive patterns of marine biota and their dependents over time (Simpson 1991, pers. comm. L. Smith and A Heyward 2003)

Surface water chemistry data is limited in the NW Shelf region (Glenn, 2004), but water temperatures from satellite derived sea surface temperatures (Figure 2.10, 2.11 and appendix 2.4) have been acquired since 1991 by the US National Oceans and Atmospheric Administration (NOAA). This record shows seasonal variation due to the southeast trade winds, the inter-related seasonal flux of the ITF and yet to be determined Indian Ocean influences.

Many of the measurements of the ITF have been made in the top 400 -500 m. Long term current measurements by Molcard et al. (1996) however, show that velocities increase below the thermocline (500m), with a maximum flow at 1400 m, suggesting that deep water exchanges are also significant (Baptiste et al. 1997). Gordon et al. (2003) identifies a large percentage of the ITF is stratified and, in fact a cool water mass (15⁰C) flows into the Indian Ocean at 400+ m depth. Gordon indicates that this due to a 'plug' of fresh water restricting the warmer surface flows through the Makassar Straits.

2.3.2 Changes in Sea Level.

Glaciers and ice sheets have oscillated throughout the Quaternary in response to astronomical cycles relating to the axis of the earth, the earth's orbit, and the precession of the earth's orbit (Broecker and Denton 1990). These oscillations have occurred at primary periodicities of 20ky, 41ky and 100ky, which are termed the Milankovitch cycles, after their discoverer. Sea level has fluctuated between -130 m and +5m in accordance with the occurrence of these climactic cycles.

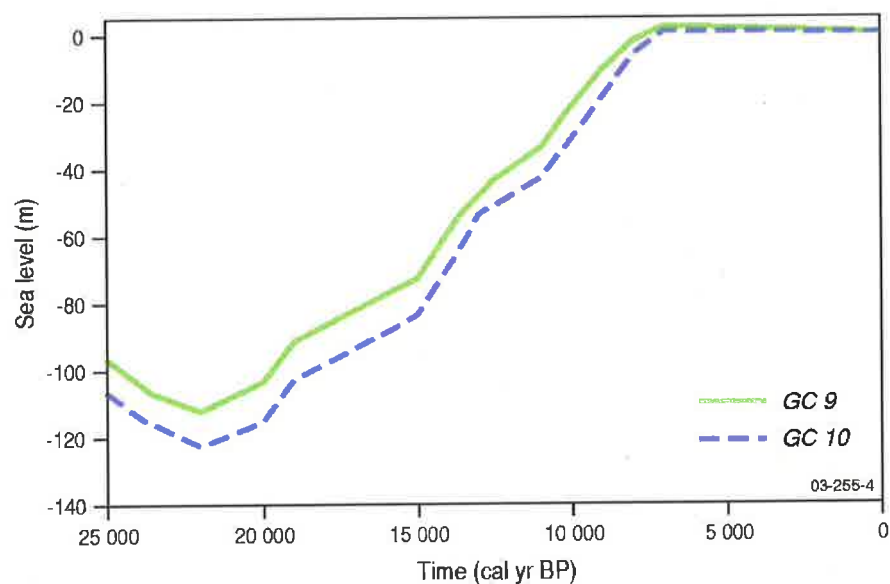


Figure 2.15 Sea Level change of the Bonaparte Shelf over the past 25000 years, based on isotopic records from two gravity cores (GC 9 and 10) from Yokoyama et al (2001).

The changes in regional sea level experienced in north-west Australia throughout recent geological history have been assessed by Chappell (1994), Lambeck et al. (2001, 2002) and Lambeck and Chappell (2001), Yokoyama et al. (2001 a, b) amongst others. The sea level for the past 25 Ka has been calculated using the oxygen isotopic values of biogenic carbonates obtained from gravity cores, and is estimated to have been located at $-124\text{m} \pm 4\text{m}$ in the Bonaparte Depression during the LGM (Yokoyama 2001) (Figure 2.15). At this time, much of the NW Shelf would have been subaerially exposed (Figure 2.16).

These records are based on the isotope record of benthic foraminifera and molluscs whereby during the growth phases, the animal records the oxygen isotope value of surrounding sea water in the construction the shell or test. If and when the values in the water alters, this change is recorded in the skeletal structure of the biota.

The isotope value or ratio of ocean water changes over time for several reasons.

First order principals demonstrate that the ratio of δO_{16} and δO_{18} varies in relation to the amount of water being bound up in the polar ice caps eg. large ice caps = isotopically heavier sea water which is also observed as changes in the relative sea levels, but it is not that simple (Shackelton 1987). Variations in isotopic values occur and in the case of the Bonaparte Shelf may be isotopically heavy is due to high evaporation rates. This phenomena takes place whereby the isotopically lighter Oxygen isotope (δO_{16}) is more prone to evaporation due to having a lighter molecular weight.

The waters of the Bonaparte Shelf are isotopically mixed due to the following.

- 1 Water flowing onto the shelf is largely derived from both the isotopically light ITF and terrestrial environment.
2. Little upwelling from the deeper isotopically heavy Indian Ocean water occurs.

Yet these values are subject to seasonal variation, due to evaporation being at least twice that of precipitation (Wyrski 1961) and with the heavy monsoonal precipitation. Therefore biogenic isotope records in this present day tropical shelf, record a range of signals.

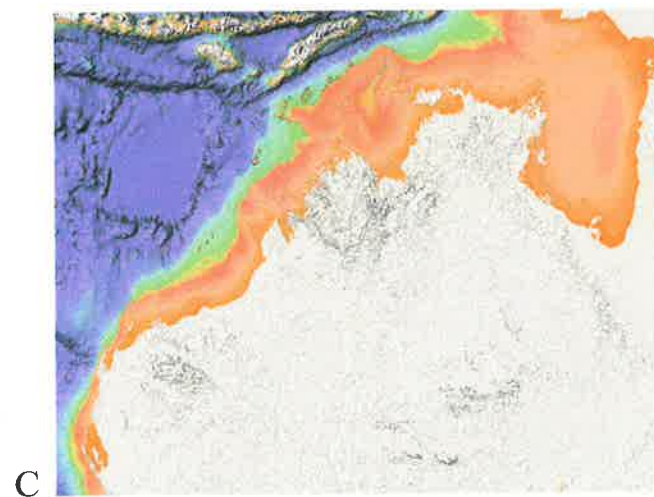
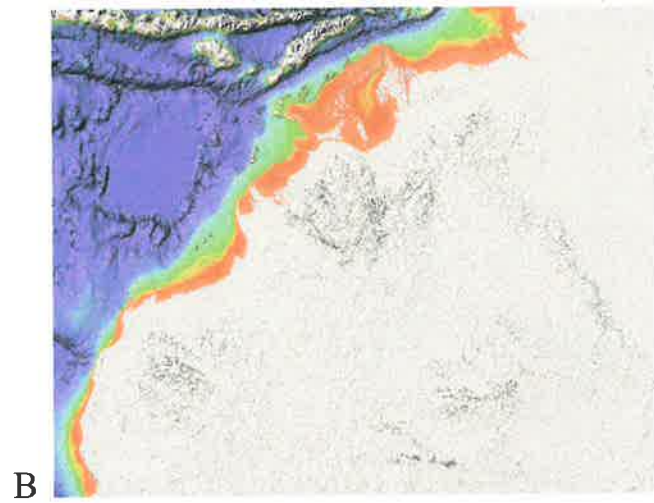
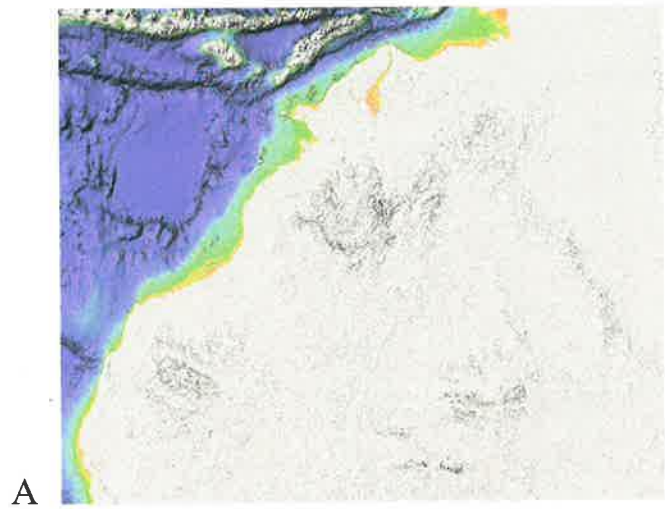


Figure 2.16 Sea level at -124m (a) 70m (b) and present day sea level (c) generated for this study show the extent of shelf area covered during times of sea level highstand.

2.3.3 Oceanic Flow and Tectonics.

The closing of the Indonesian seaway from the Pacific to the Indian Oceans (Linthout et al. 1997) started ~20Ma as the Indian-Australian Plate headed northwards into the Eurasian plate and the SW Pacific plate converged from the east (Figure 2.17). At 8 Ma, the Indian -Australian plate was still moving NNE into the Eurasian plate at 1cm/^{yr} (Linthout et al 1997) and the SW Pacific plate maintained its collision direction (Figure 2.18). The exposed land masses and shallowing seas continue to restrict the seaway, as the plate convergence persists (Figure 2.19).

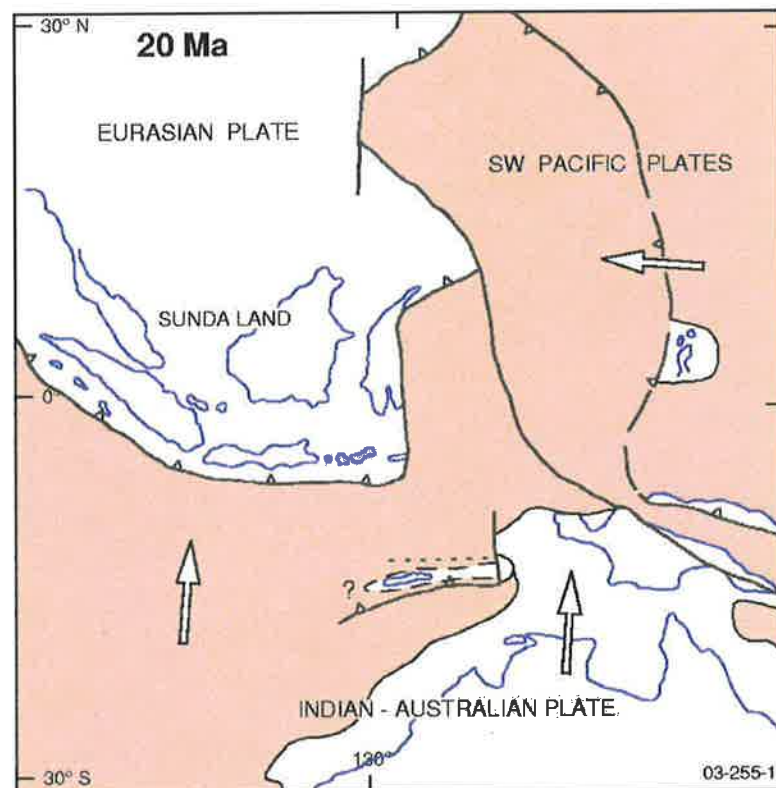


Figure 2.17 Tectonic movements at 20 Ma Modified from the regional appraisal by Linthout (1997) to show the constriction of the Indonesian sea way as the Indian-Australian plate moves to the north.

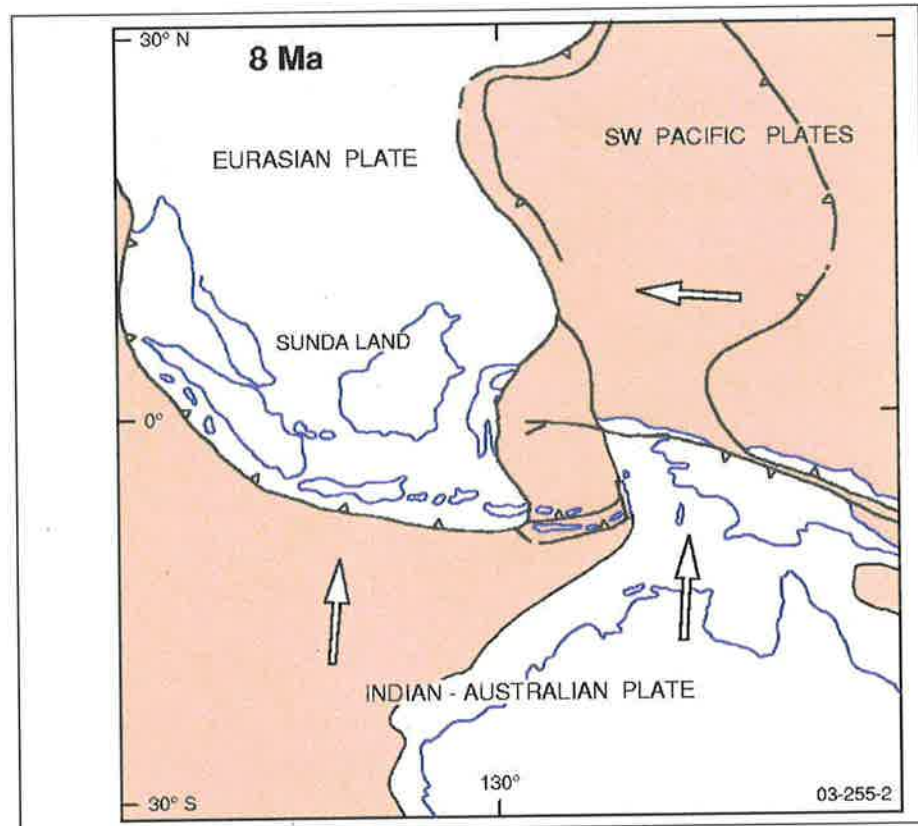


Figure 2.18 Tectonics at 8 Ma. Modified from the regional appraisal by Linthout (1997) indicates the further constriction of the Indonesian sea way and its potential for inter-ocean flow.

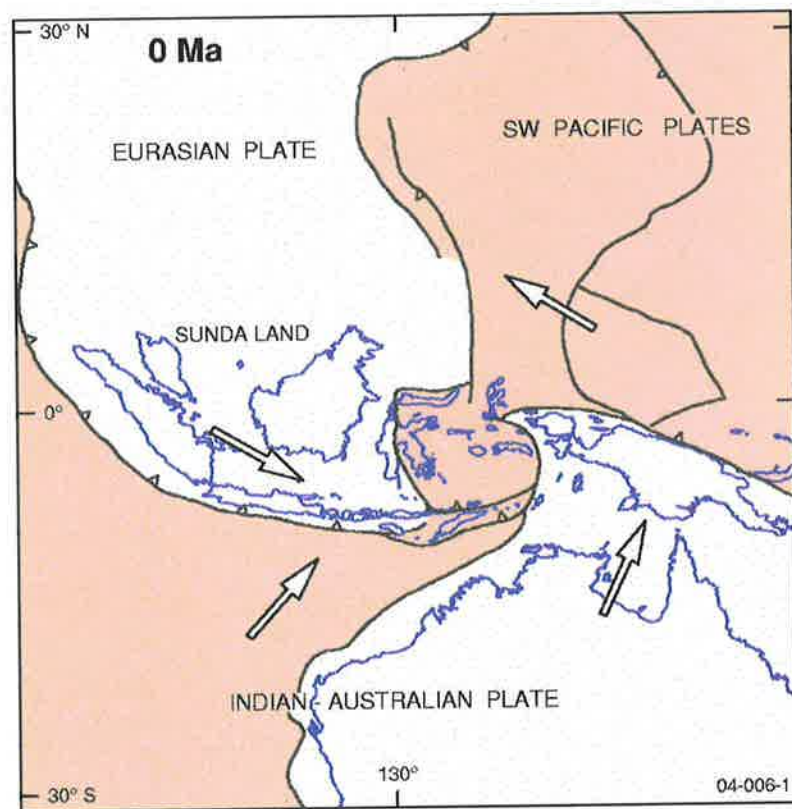


Figure 2.19 Present day tectonics modified from the large scale study by Heflin et al. (2003) to show current tectonic trends of the Indian – Australian and SW Pacific Plates

2.3.4 Tides

The semi-diurnal macro-tidal regime encountered on the northwest shelf is governed by the Indian Ocean (Wyrski 1961). For a regional perspective, Ashmore Reef to the west of the region has a mean spring range of 4.75m, and Troughton Island 4.8 m (Figure 2.20, Flinders University, National Tidal Facility). Mean spring tides increase up to 9 m towards the coastline, and offshore the tidal direction of ebb and flood tides is north-east / south-west (Marshall et al. 1994). The southern Joseph Bonaparte Gulf, has tidal ellipses running in a south-east / north-west direction (Lees 1992).

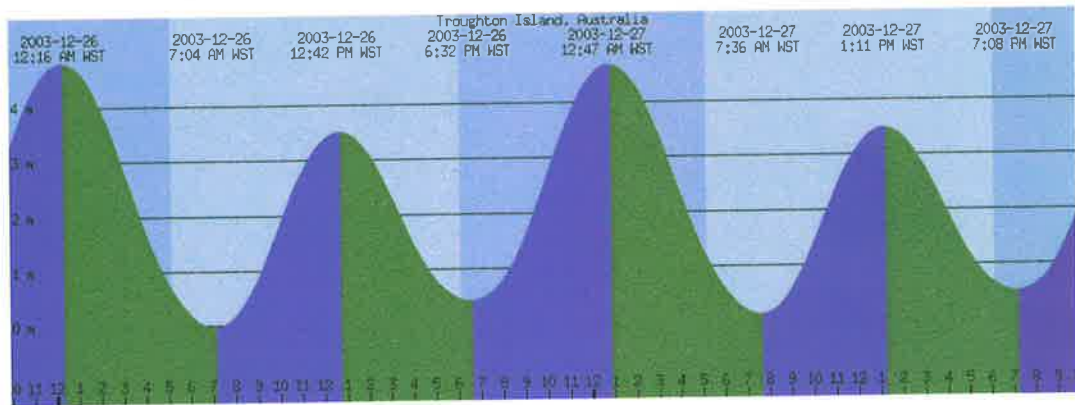


Figure 2.20 Tidal regime of Troughton Island, Australia 13.7500° S, 126.1333° E
Flinders University, National Tidal Facility.

2.3.5 Sea surface currents

Generally the regional surface currents are driven by the prevailing winds. These are predominantly from the east and south-east during the dry season and from the north east north and north west during the monsoonal season (Figure 2.21).

Offshore observations by the author, and tidal wind /wave current descriptions by Royal Australian Navy (1978) in Lees (1992), all noted regional offshore surface currents flowing up to 2 – 4 knots and nearshore in the river mouths from 3.8 – 5.8 knots.

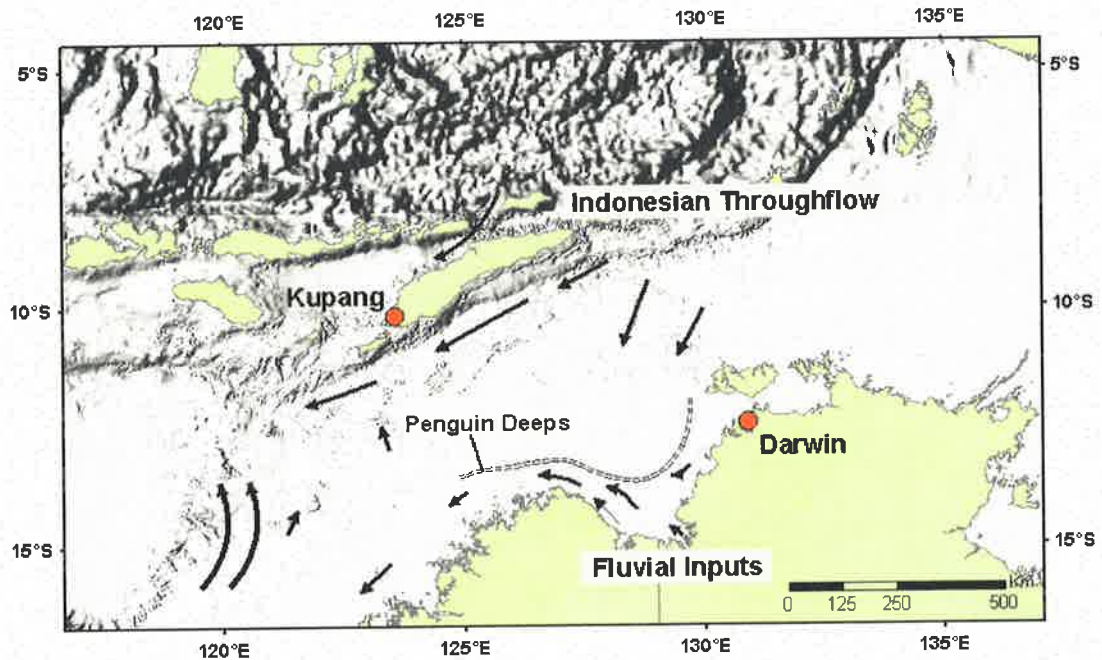


Figure 2.21 Prevailing Surface Currents of the Bonaparte Shelf.

Oceanic inputs from the north, fluvial contributions, tidal movements coupled with off shore winds promote a near shore circular current across the bottom of the Bonaparte Gulf. Landsat Thematic Mapper (TM) imagery acquired for this study (Discussed further in Chapter 3, Figure 3.36), visually confirms this westerly flow. Additionally work by Lees (1992), shallow sea floor morphology from both Geoscience Australia bathymetry and from unpublished Cambridge Gulf Diamond reports, coupled with on site observations throughout the Joseph Bonaparte Gulf and Cambridge Gulf, all indicate the presence of a quasi-circular near shore current, which travels southward turns clockwise and flows west into the deeper Indian Ocean after travelling through / across the Penguin Deeps channel.

2.4 Climate

2.4.1 Climate Introduction

Long term, robust climate records are scant in the region, with the exception of data collected by the Bureau of Meteorology (BOM) at Troughton Island (13.8° S 126.2° E), approximately 70km south of the study area, and Kupang (10.10° S 123.40° E at 108 m) (Figure 2.22), Indonesia, approximately 300 km to the north.

The meteorological conditions, including temperature, precipitation and wind, which characteristically prevail on the Australian northwest shelf have changed during the Late Quaternary (van Andel and Veevers 1967), (Bowler et al. 2001) with changes in sea level and the onset of the monsoonal regime 14000 years ago (Wyrwoll and Miller 2001).

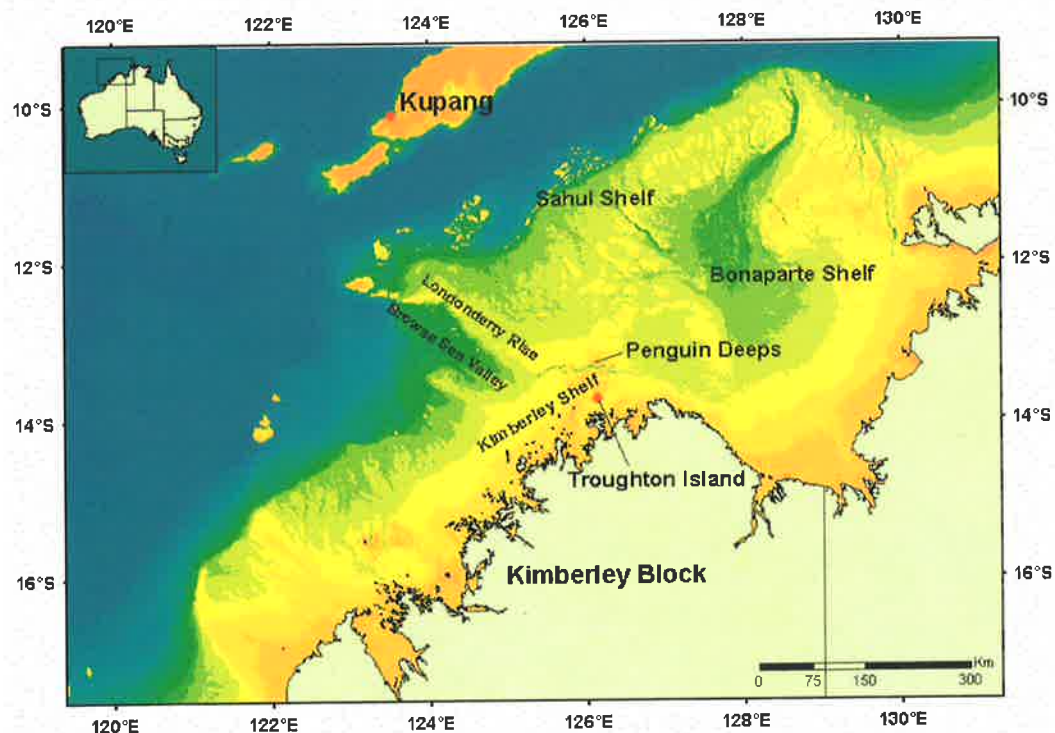


Figure 2.22 Location map with Troughton Island and Kupang where the regional climate record has been established for this study.

2.4.2 Present Day Conditions

Currently, the northwest Shelf lies under the influence of the tropical monsoonal system, with 88% of the rainfall occurring during the Austral summer and a dry season occurring during the Austral winter (Figure 2.23). Conditions are warm and humid throughout the year, with regional temperatures ranging from 22 °C to 36.4 °C. (Figure 2.24).

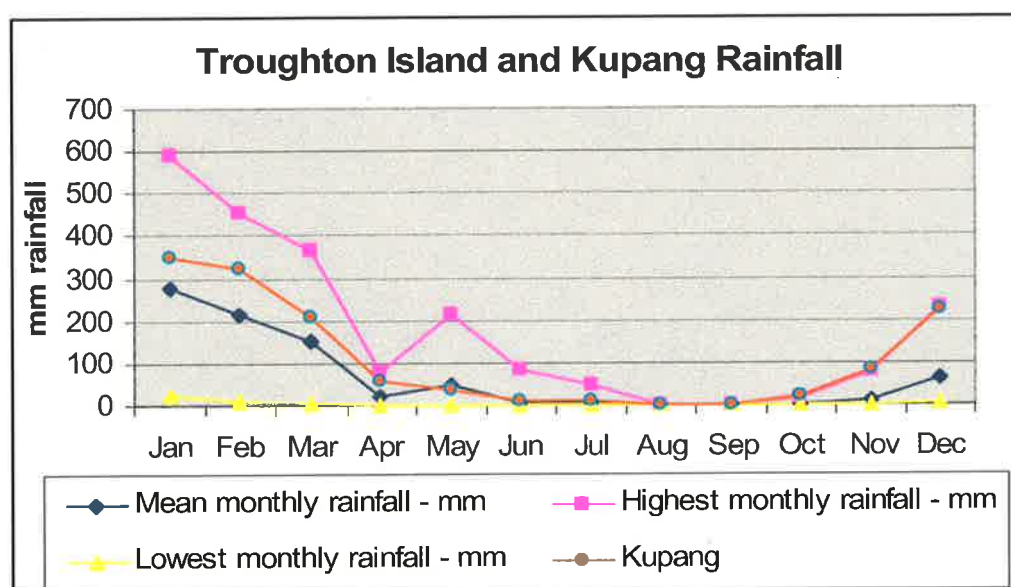


Figure 2.23 Rainfall of Troughton Island (BOM Data) includes mean monthly rainfall, Highest monthly rainfall and Lowest monthly rainfall. The record for Kupang (Indonesia) records the average rainfall.

Monsoon rains occur between November and March, with storms and cyclone systems passing across the region, generally from the north. The robust more comprehensive Troughton Island climate record, shows that the monsoonal precipitation is heavy during the summer months (Figure 2.23), with 702 mm (mean averaged over 17.5 years) falling during December - March, and with cooler mid-year months being almost precipitation free with 2.7% mean averaged

rainfall during June - November. This condition results from the offshore south-east trade winds passing across central Australia, upon which they lose much of their original moisture (Tapper and Hurry 1993). This study indicates that these winds also play a pivotal role in the direction of the surface currents in the near shore environment.

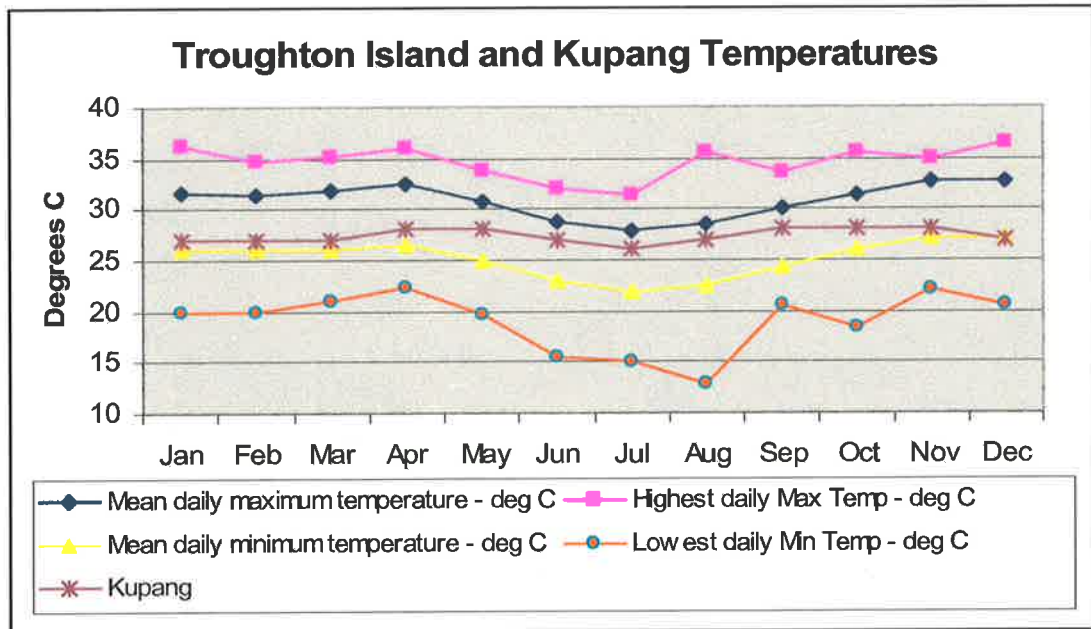


Figure 2.24 Temperature of Troughton Island, (BOM Data) including Mean daily maximum, mean daily minimum, highest daily maximum lowest daily minimum and for Kupang Indonesia, the average daily temperature.

Humidity (Figure 2.25) is highest in February, and lowest in winter. Wind speeds (Figure 2.26) have two seasonal peaks. The first, and highest, occurs in December January during the most active monsoonal conditions and the peak cyclone season, the second in May-June-July coincides with the onset of the south-east trade winds.

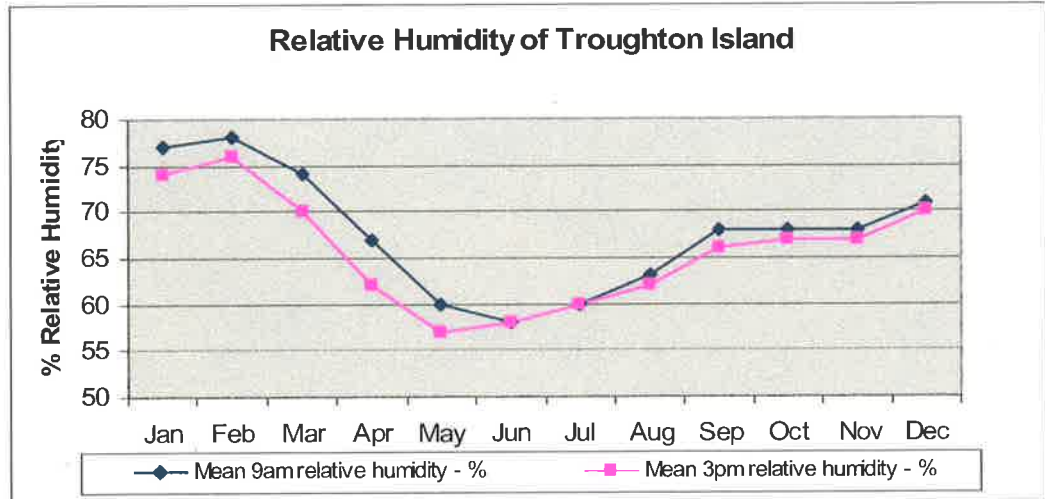


Figure 2.25 The mean Relative Humidity over 16 years, 9am. and 3 pm., Troughton Island (BOM data), has a direct relationship with the monsoonal inputs and the wind speeds throughout the year.

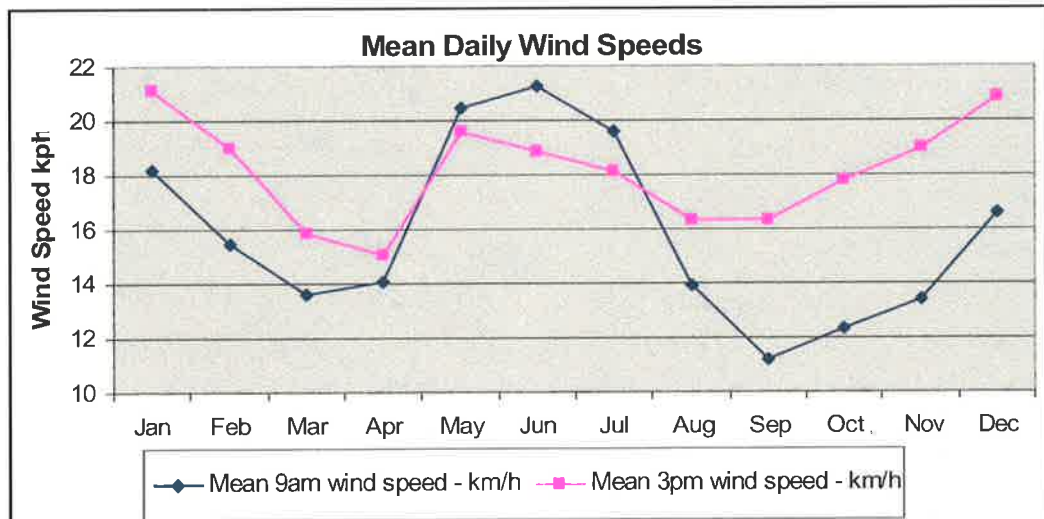


Figure 2.26. Mean Daily Wind Speeds over 19 years, 9am. and 3pm., Troughton Island (BOM Data). The onset of the southeast trade winds are clearly evident in the middle of the year.

Previous work by (Wyrski 1961) denotes that the regional offshore Bonaparte

Basin experiences an excess of evaporation over rainfall by a 2.6:1 ratio, with annual precipitation of ~700mm, and evaporation of 1816mm. Regionally

thunderstorms are experienced ~85 days/^{yr} (van Andel and Veevers 1967).

Closer to the Australian mainland, Troughton Island experiences a mean number of 49.2 rainy days/^{yr}, whereas Kupang, in the driest region of Indonesia, averages 34 rainy days/^{yr} (BOM).

2.4.3 Cyclones

Cyclones are one of the most destructive natural threats to the regional coastal communities and economies in north-west Australia (Nott and Hayne 2001) along with tsunamis. Cyclones develop over warm tropical waters with sea temperatures above 26 – 27° C to a water depth of 60m (Ryan et al. 1992), in areas of very low pressure. Tropical cyclones are sustained winds greater than 63km/h and a "severe tropical cyclone" produces sustained winds of at least 118 km/h (Figure 2.27).

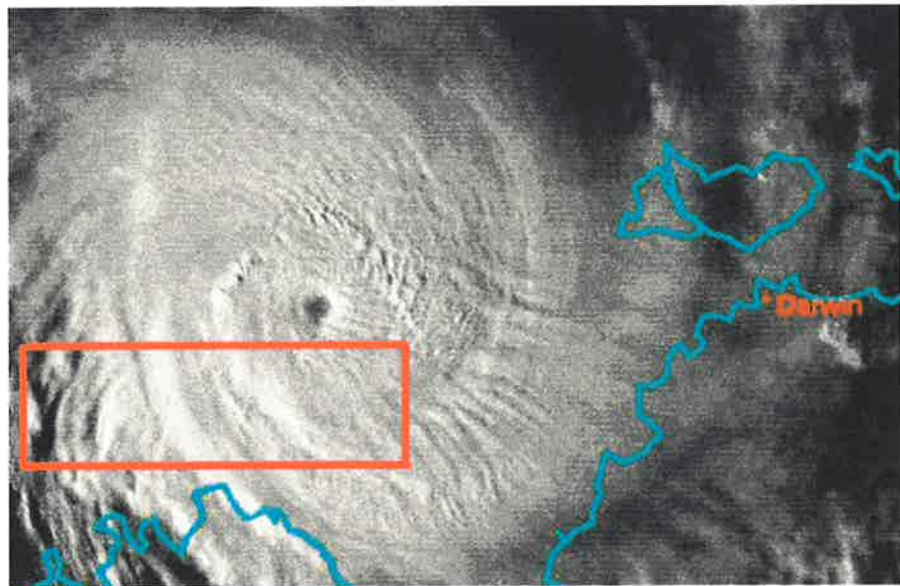


Figure 2.27 Cyclone Thelma, Category 5 over the Timor Sea (Image courtesy BOM)
The red box highlights the study region.

2.4.4 Cyclone frequency.

A number of cyclones have gone undetected over the past 100 years due to a lack of climate observations. Increases in frequency during this time probably reflect the improvement in reporting and tracking methods over time. European mariners have been very aware of the dangers associated with cyclones for centuries (Marsden 1999) recording the impacts in their journals. Yet the first official recording of an Australian cyclone was documented by the Australian BOM was in 1912 with ~1 - 10 cyclones /yr recorded (Figure 2.28) thereafter up to 1955,

and then $\sim 7 - 19$ /yr more recently. On average, there are two cyclones per year in the Gulf of Carpentaria and 2 / yr in the Arafura and Timor Seas. Cyclone tracks appear to bend around the northern Australian coastline to form what is colloquially known as the 'cyclone alley' which runs parallel to the Australian north-west coast (Figure 2.29).

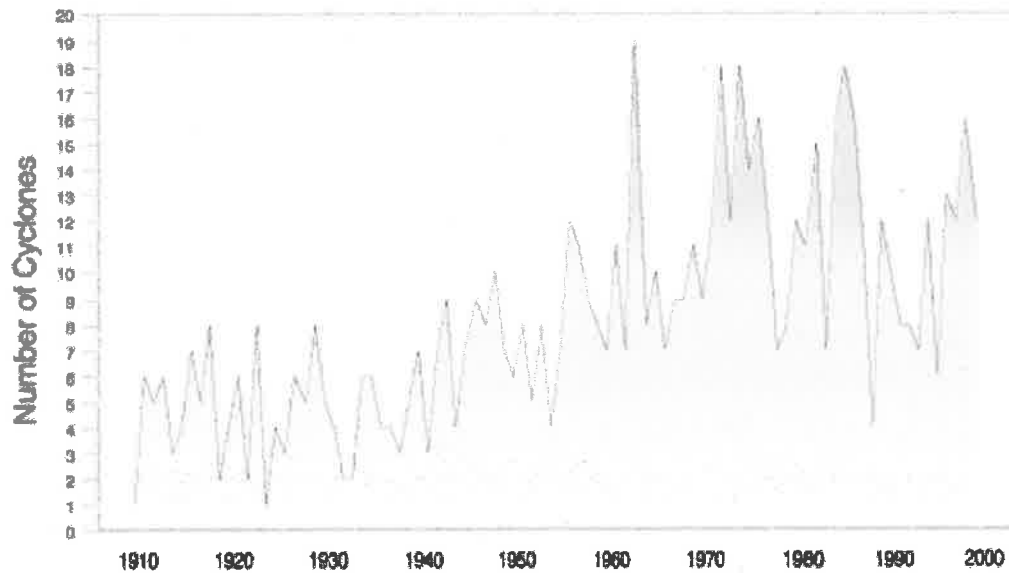


Figure 2.28. The annual occurrences of tropical cyclones in the Australian region (105–165°E) July 1909 - June 2000. BOM

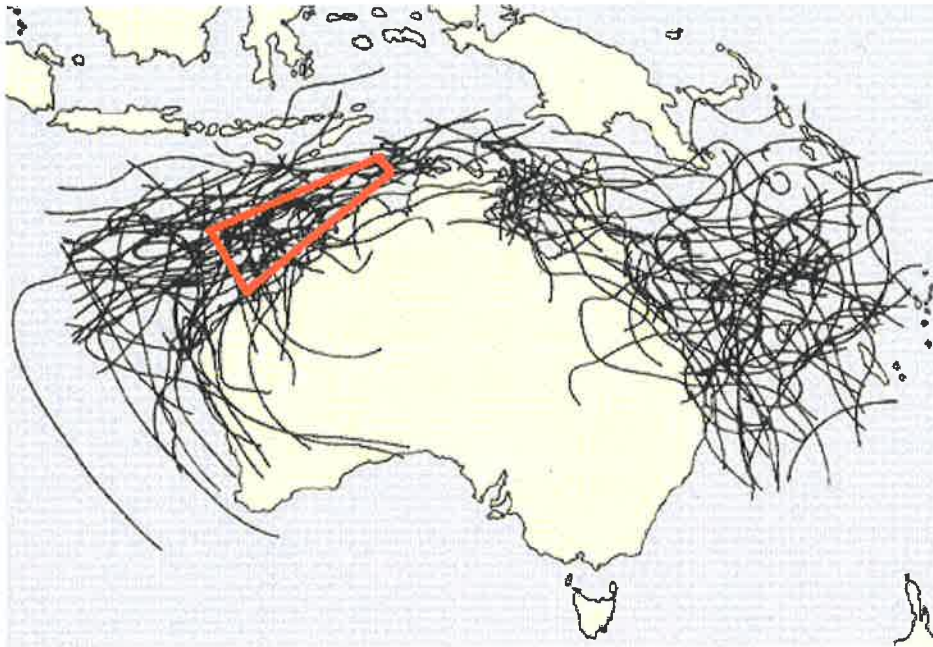


Figure 2.29 Tropical cyclone tracks in the Australian region, 1970–80 (Image courtesy of Australian Science and Technology Heritage Centre 2003) Red box shows 'Cyclone Alley'.

2.4.5 Two examples of severe tropical cyclones over the study region.

1. Tropical Cyclone 'Thelma' 6 – 11 December 1998

'Thelma' was one of the most intense tropical cyclones to be observed off the Australian coast. Forming in the Arafura Sea, it travelled west-north-west, intensifying rapidly into a Category 5 cyclone (Figure 2.30). It then drifted to the south–south west and again in a southerly direction across the Timor Sea before crossing the north Kimberley coast.

2. Tropical Cyclone Vance, 17 - 24 March 1999,

Initially located off the north Kimberley coast on the 18th of March this cyclone moved west southwest at first, then southwest (20th - 21st). Intensifying steadily and became a Category 3 cyclone late on 19th (Figure 2.31) It was further upgraded to a Category 5 overnight on 20 March. A category 5 cyclone has winds gusting to more than 280 km/h.

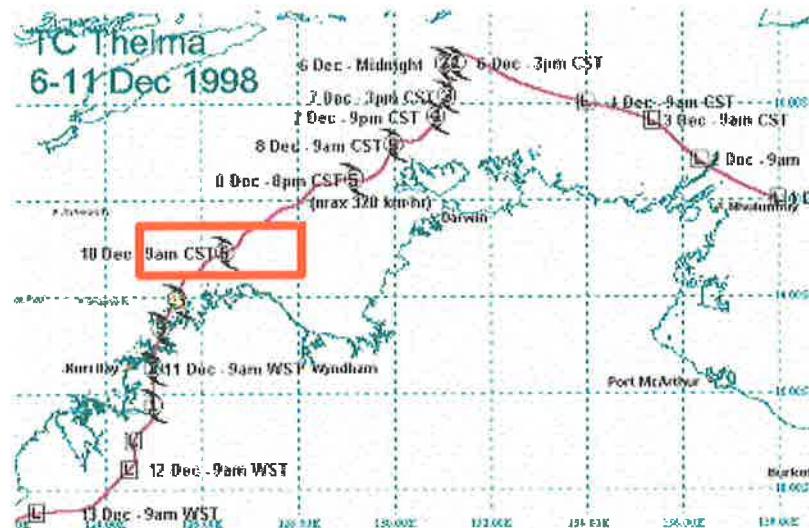


Figure 2.30 Track of Tropical Cyclone Thelma 6 – 11 Dec 1998.
Study region in red box (Image courtesy of BOM)

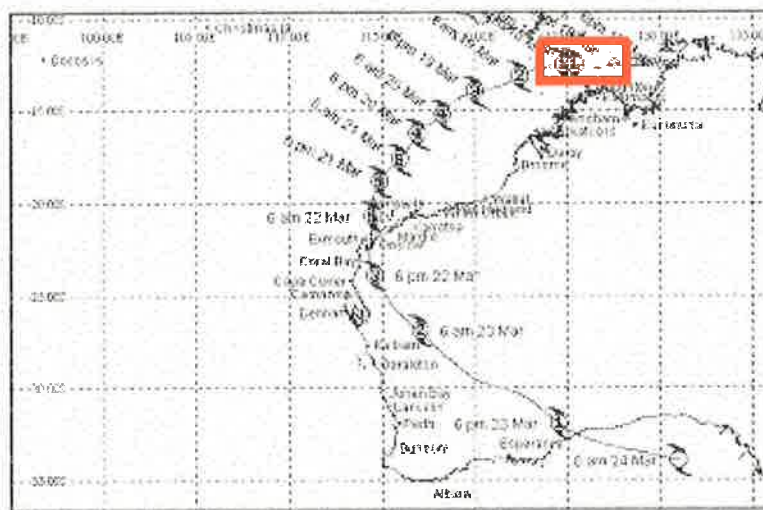


Figure 2.31. Track of tropical Cyclone Vance. Red box shows study region.
(Image courtesy of BOM)

2.4.6 Atmospheric circulation

Changes in atmospheric circulation have a direct relationship to local and regional temperature and precipitation levels. Driven by solar energy, the wind is modified by the extent of nearby land, sea and terrestrial topographical features (Williams et al. 1998). Present day south-east trade winds are strongest in mid-year (May –

August) at 20 - 25 knots (Figure 2.26) with light southerly conditions and storms from the north during the November - February period (Figures 2.26, 2.32a, 2.32b). The winds have a different emphasis in intensity and timing during glacial periods.

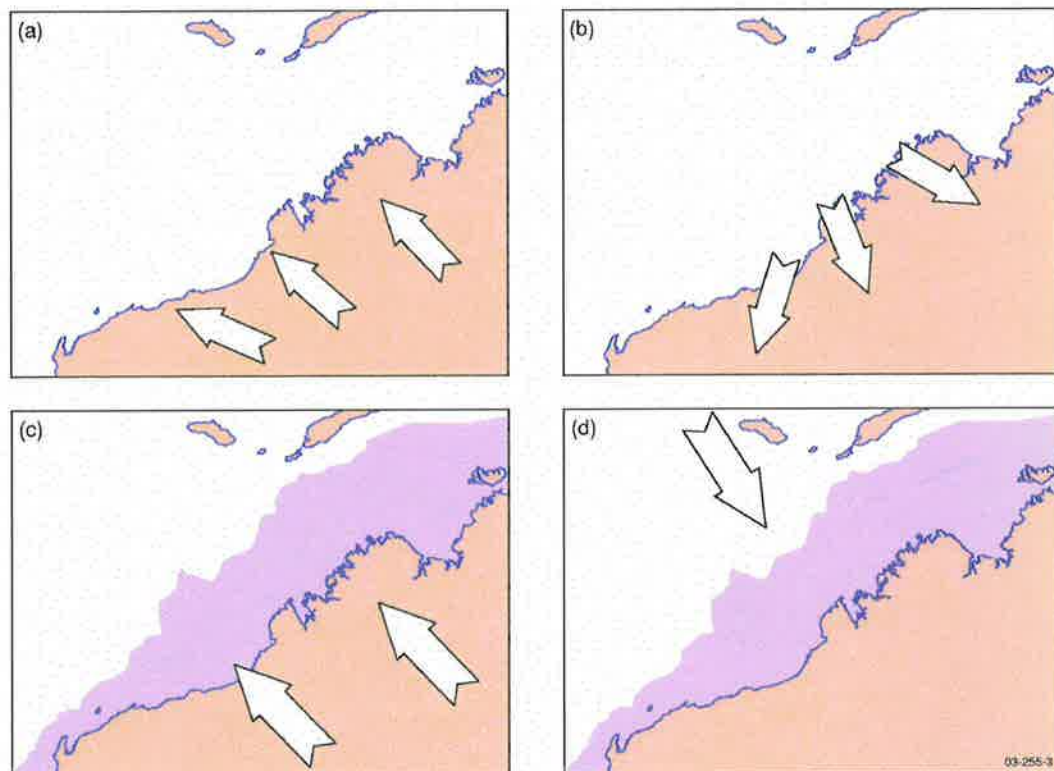


Figure 2.32 Modern seasonal wind shifts, 'A'. Jan, 'B'. August, 'C' ~Jan 'D' ~August during the Last Glacial Maximum (modified from Gingele et al. 2002). The coastline at LGM is illustrated in the light blue shading. Larger arrows indicate comparatively stronger winds.

2.4.7 Climate change of the Late Pleistocene - Holocene.

Rigorous scientific study of recent climate change for Northwest Australia is still in its infancy. Work to date includes many proxy investigations of climate using:

- Cheniers (Lees 1992)
- Lake and flood deposits (Rognon, and Williams 1977), (Wyrwoll, and Miller 2001), (Bowler et al. 2001 (Pack et al. 2003).
- Atmospheric circulation and thermal convection (Shumeister, 2000).

- Marine sediment cores (Wells, and Wells 1994; Hantoro 1997; Veeh et al. 2002; Pack et al. 2003; Yokoyama et al. 2001; De Deckker et al. 2003; Gingele et al. 2001).

Coral reef morphology and C^{14} dates (Glenn 2004; Glenn and Collins 2004).

- Plunge pool morphology (Nott and Price 1994)
- Oceanography (van Andel and Veevers 1967; Godfrey et al. 2000).

The region has thought to have been tectonically stable over the recent geological past it is a preferred location for far field sea level studies (Pratt et al. 2001), which are in turn intrinsically linked to climate.

The Torres Strait (Figure 2.33) was closed at times of lower sea level during the Last Glacial Maximum (LGM) from 30 – 19 ka (Lambeck et al. 2002). And due to reduced input from the Western Pacific Warm Pool (WPWP) via the ITF, cooler Indian Ocean water would have been able to penetrate further northwards and have a longer residence time in the Timor Trough (van Andel and Veevers 1967).

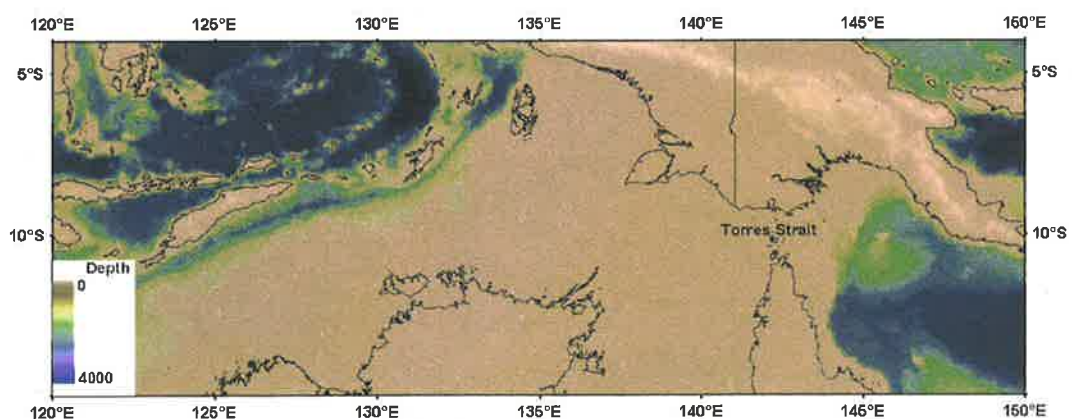


Figure 2.33 The Torres Strait at the northern eastern tip of the Australian continent and the conduits at Last Glacial Maximum. The khaki colour denoting the extent of the land surface.

This Indian Ocean water was colder by $\sim 1-2^{\circ}\text{C}$ (Chappell 1994, Barrows et al. 1996) and adjacent to a land mass that was larger due to the lower sea level exposing one of the world's largest continental shelves. Both of these factors would contribute to reducing potential evaporation which in turn would reduce the regional precipitation potential. This scenario leads to a first order understanding of reduced precipitation at colder times of lower sea level which has environmental ramifications, including changes in terrestrial vegetation types. Another key environmental consideration for this study is the onset of monsoon activity and cyclone frequency, each of which plays a part in controlling fluvial derived terrestrial sediment input (Figure 2.34a, b). Work by Wasson (pers com 2003) indicates that erosion rates are high at the onset of the annual monsoon, and after other extended periods of minimal rainfall.

The overall rainfall in summer and winter was lower during the Pleistocene (Kershaw 1978). Studies on grass types and distributions (work in progress by Miller) indicate that the wettest phase in the past 150ka occurred during the last interglacial and to a lesser extent at 60ka and in the Holocene. A paucity of robust dating has, however, made it difficult to assemble a good Holocene record, and there is little evidence of monsoonal activity during the early Holocene. Wyrwoll et al. (2001) acknowledges a subdued monsoonal activity in geological recent times, and lake deposits indicate that it has been relatively stable for the past 5ka. These studies correlate with large flood events noted in the northern Australian waterfall plunge pool morphology work (Nott and Price 1999).

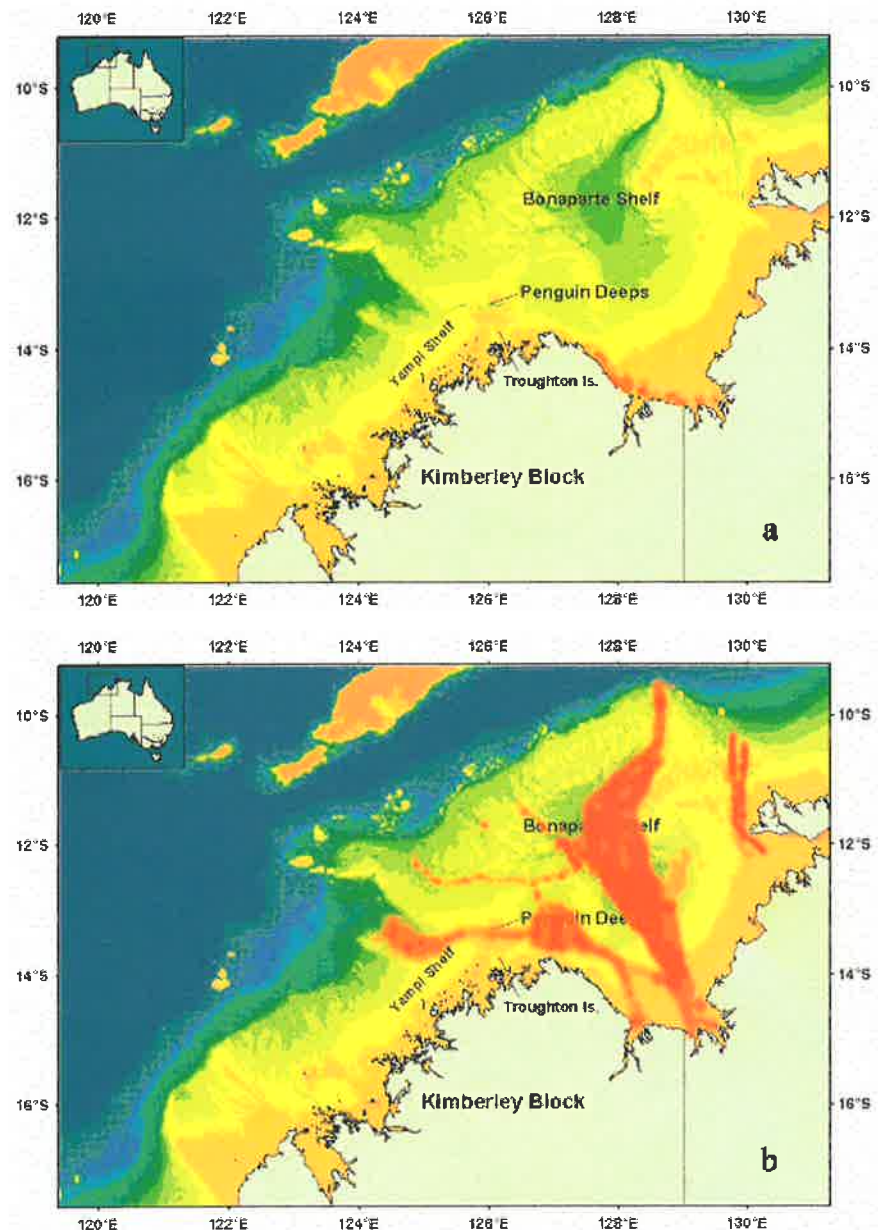


Figure 2.34 Depositional settings, (a) At high SL and (b) at low SL. The sediment arriving on the near shore environment during sea level highstands is not moved across and off the shelf as it is at times of sea level lowstand.

Work by Wyrwoll et al. (2001), Bowler et al. (2001) further suggests that a monsoon has been present for the past 14ka, with a slight reduction in intensity during the past 5ka. (Bowler et al. 2001) also states that late Quaternary changes from drier to wetter conditions were more extreme than experienced today,

perhaps because of changing evaporation potential as the region's oceanic regimes were being reorganised during sea-level rise. Concurrent variations in monsoonal conditions probably occurred, including abrupt transitions and strong interaction with SST in the adjacent and distant oceans and the surface hydrology of the Asian-Australian land masses (Meehl 1987). These climactic variations have been the subject of large international studies (CLIVAR, 1997) which concentrate on the feed-back mechanisms and factors which contribute to monsoonal timing, distribution and formation. Other factors such as snow cover or soil moisture may exert impacts on monsoon variability, either directly and/or indirectly through feedback processes with the El Nino-Southern Oscillation (ENSO).

Quasi-periodic oscillations occur in a wide range of monsoon variables including rainfall, surface pressure, wind, SST and subsurface water temperature. Several theories exist as to their origin, including variations on air-sea-land interaction with the monsoon regions. The relationship with the Tropospheric Biennial Oscillation (TBO) and ENSO is uncertain (Goswami et al. 1992), but others, including (Li et al. 2001) identify these two oscillations as separate modes because of their non-linear interaction.

Chapter 2.5 Water Balance Fluvial inputs

2.5.1 Regional river flows

Regional river flows in north-western Australia have a distinct seasonal pattern with annual variability resulting in a range of arid landscapes with low vegetation cover and a high soil erosion rate. The drainage division flowing into the Timor Sea has an area of 547,000 km², with ~92% of the average annual river discharge occurring in the four month period from December to March (Pettit et al. 2001). This monsoon cycle produces a mean annual outflow of 81.461 GL. (Australian Bureau of Statistics, 2003). Calculations (Lees' 1991) give a discharge load of 196×10^6 t/a. for rivers from the Victoria to the Ord (Figure 2.35). The study area receives additional inputs come from the Fitzmaurice, Berkeley and King George rivers. Yet ultimately, hydrological input is altered by annual variation in climatic conditions and the extensive regional evaporation potential in this region, which is approximately twice that of precipitation (van Andel and Veevers 1967).

The seasonal fluvial regime with its large sediment and nutrient load transport capacity visibly extends up to 70 km off shore in the case of the Fitzmaurice and Victoria Rivers, 30 km for the Keep and Ord rivers and 10 km for the Berkeley River (pers. comm, D. Skene 2003). The other smaller rivers entering the sea on the NW facing coast, have less extensive catchments. Their outflows are deflected to the northwest by the near shore coastal current regimes as seen on this studies Landsat TM images (Figure 2.36). Landsat TM images detect suspended sediments up to 65km off shore along the western side of the Bonaparte Gulf during the dry season. The sediment plume highlights the overall direction of both fluvial and marine water flow in the open marine environment.

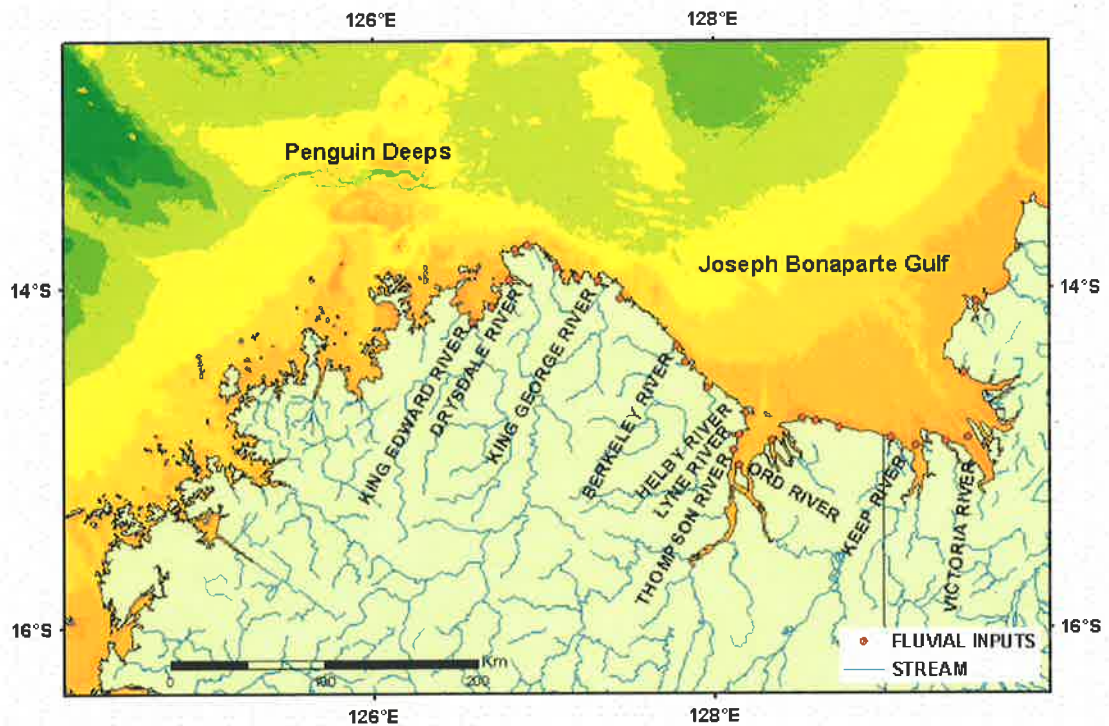


Figure 2.35 Fluvial inputs to the study region. Rivers from the far right hand side appear to add to a northerly flow during low sea level stands. Rivers from the Keep across to the King Edward contribute to the hydrodynamics and reworking of terrestrial sourced sediment.

The overall coastal current direction is clockwise. This is due to several phenomena including oceanic inputs of the Indonesian Throughflow, fluvial inputs of rivers from the Daly to the Berkeley, prevailing south east (off shore) winds, and the atmospheric Coriolis force. These forces assist in directing the water in a southern and south west direction along the north-east Kimberley coast. Here it is speculated that the water and sediment has a dynamic interplay with the ebb and flood tides creating elongate bed forms or bars, approximately parallel with the coast line and is apparent in the intermittent plume observed on the Landsat Thematic Mapper (TM) images.

2.5.2 Landsat Thematic Mapper images

The processing of the regional Landsat Thematic Mapper (TM) images, provided supporting information regarding overall hydraulic flow, the occurrences of near shore shallow banks and islands and the suspended sediment travelling along the coastline towards the west of the study area.

The composite view of the images (Figure 2.36) clearly show drainage features, a variety of intertidal and near shore bed forms and areas of open clear oceanic water. The sediment plumes in shallow water associated with the coastal environment and adjacent river mouths are best seen in the colour separated bands: one two and three (Figures 2.37, 2.38, 2.39). The top of the image on pass 108 has cloud haze yet the near shore area is predominantly cloud free.

Whilst having only four integrated regional images to work from, there are three distinct 'pulses' of sediment or sediment plumes seen across them in both the composite and the three separate band widths of the Landsat TM. These three sediment plumes are equidistant from each other with a spacing of ~70km. The plumes increase in size and decrease in intensity towards the west, most probably due to the dispersal mechanisms inherent within coastal marine environments.

The pattern or frequency of the plumes could be a response to the dynamic hydrology of the Bonaparte Basin, most probably, the tidal influence. As the Landsat TM images are from the dry season, no significant fluvial inputs are anticipated let alone presenting a rhythmic arrangement. The most probable

explanation for their existence, is the reworking / re-suspension of near shore sediments by the regions dynamic tidal cycles.

A model for this occurrence, is that once the dynamic balance of opposing water masses (tide versus the wind and ITF related shelfal currents) within the water column is disrupted, the sediment is released from the area and the subject to the over riding current regime.

Landsat (TM) imagery acquired for this study (Figure 2.36), indicates a westerly flow of the southern Bonaparte Shelf waters and the sediment load is easily distinguished in bands 1,2 and 3. these bands correlate to water depths of 3-5m, 10m and >15m. The sediment load in this dry season scene appears to be mobilised in several pulses. This may be a tidal response to the prevailing current. Additionally work by Lees (1992), shallow sea floor morphology from both Geoscience Australia bathymetry and from unpublished Cambridge Gulf Diamond reports, coupled with on site observations throughout the Bonaparte Gulf and Cambridge Gulf, all indicate the presence of a quasi-circular current on this part of the northwest shelf. This current is promoted by ITF water entering the Bonaparte Gulf shelf from the north which travels southward turns clockwise and flows west into the deeper Indian Ocean after travelling through / across the Penguin Deeps channel (Figure 2.21).

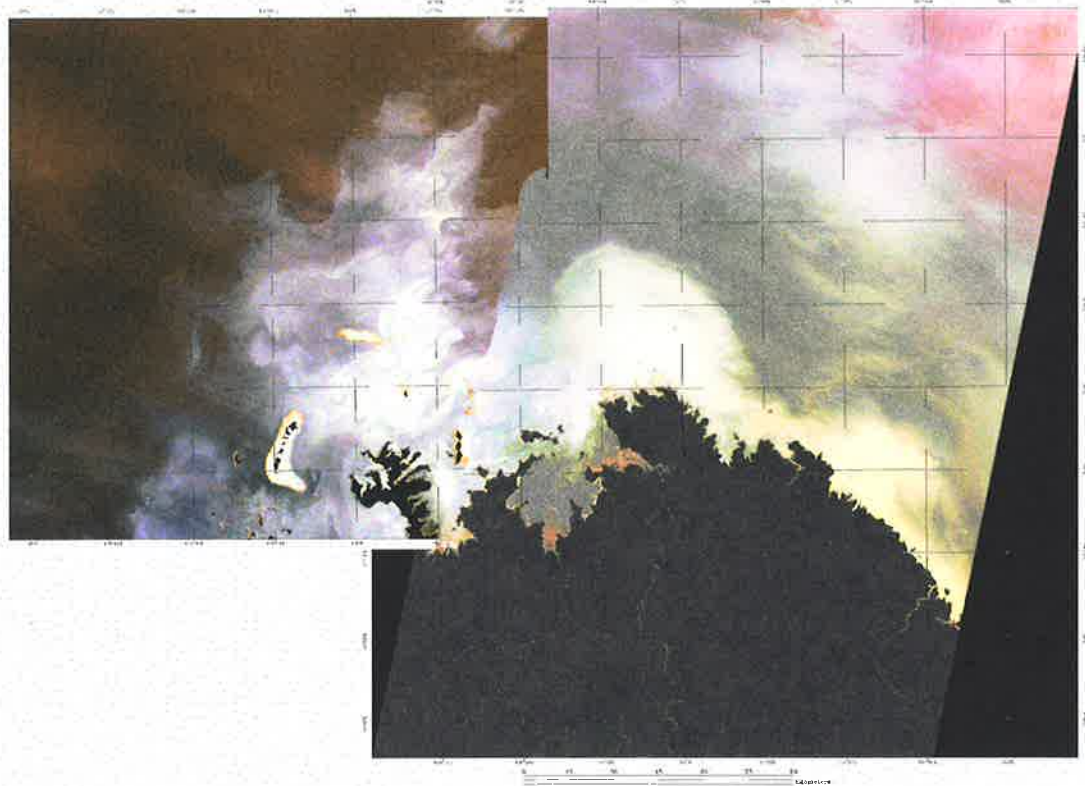


Figure 2.36 Landsat TM acquired for this study shows a strong sediment plume on the left hand side (northern Kimberley region). Two more discrete plumes are noted along the eastern Kimberley coastline.

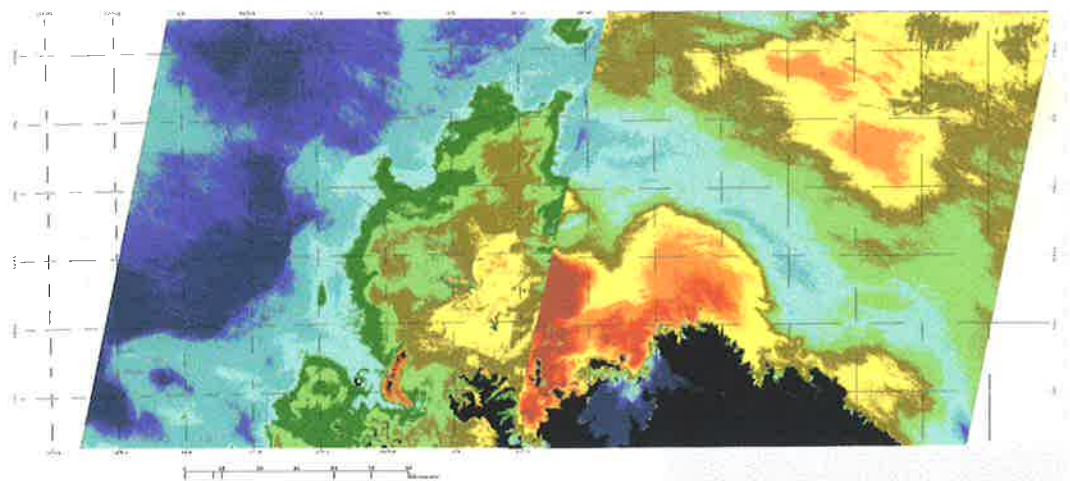


Figure 2.37 Landsat TM Band , 1 Identifies phenomena in the 15 – 30 water depth range.

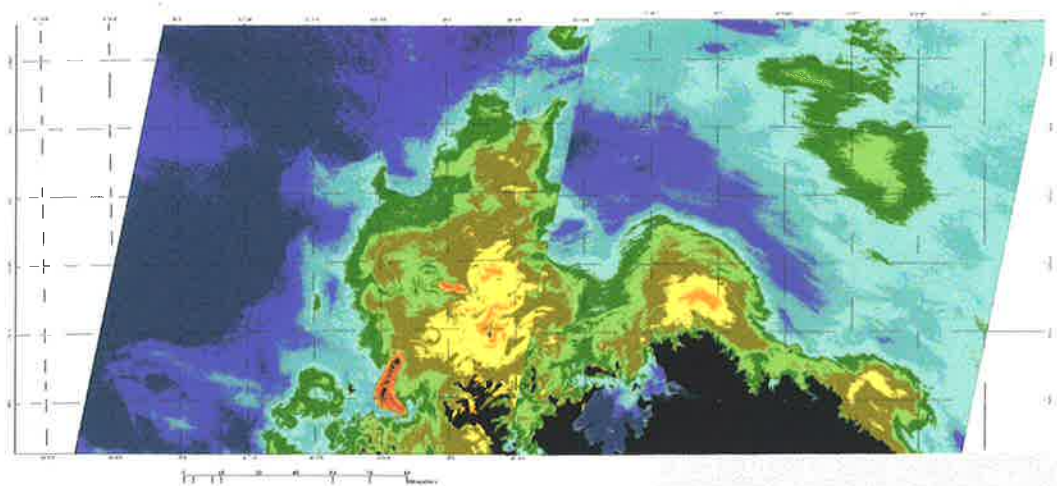


Figure 2.38 Landsat TM Band 2, Best for phenomena in water depths of ~10m.

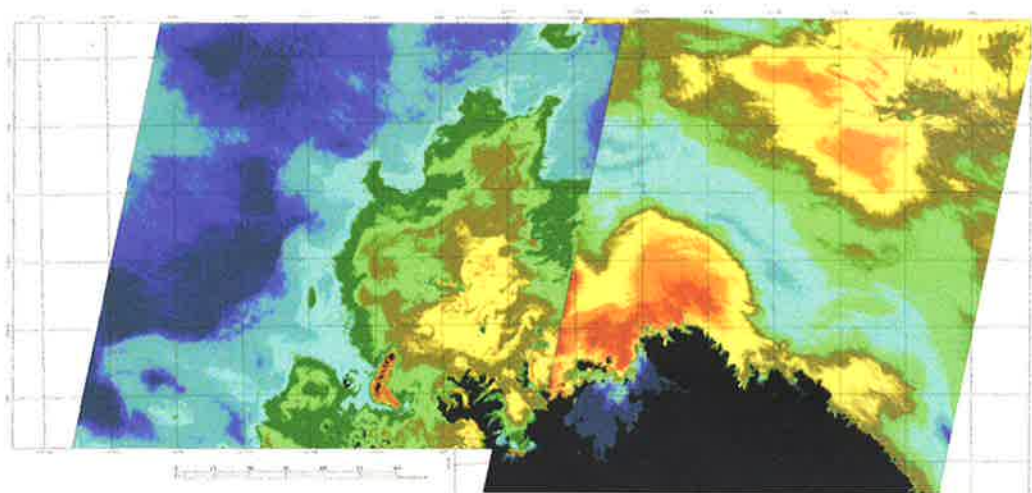


Figure 2.39 Landsat TM Band 3, Best for phenomena in water depths of 3-4m.

2.6 Terrestrial inputs

2.6.1 Fluvial derived sediments

Twenty two rivers and creeks drain into the south-west Bonaparte Gulf from the Keep River to the King Edward River (Figure 2.35 Appendix 2.5). One of the main entry points of terrestrial sediments to this part of the Bonaparte Basin is the Ord River (Figure 2.40). A comprehensive description of the main characteristics of the tropical Ord River delta is given by Coleman and Wright (1975). Under hot and dry seasonal monsoonal influences, the Ord River discharges its waters in a narrow and elongated basin dominated by the Cambridge Gulf (Figure 2.40).

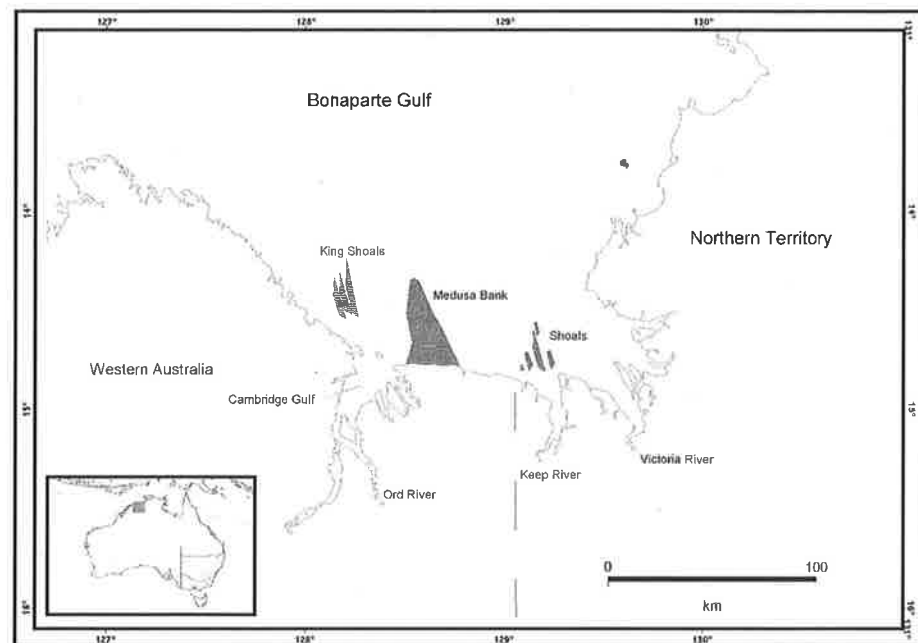


Figure 2.40 The Ord River Mouth (modified after Clarke et al. 2000).

The mouth of the Ord River and immediately seaward, is filled by lineal sediment bodies, parallel to the flow direction and related to the powerful tidal transport patterns. The closed shape of this basin and the sediment input from the river, results in the formation of long, linear tidal sand ridges oriented normal to the shoreline trend. These tidal ridges have an average length of 2 km and a width of 300 metres and their orientation indicates the dominant hydrological regime (D. Skeen, pers com 2004).



Figure 2.41 Onshore Geology of Northwest Australia.
(Used with permission of the CEO of Geoscience Australia).

Bonaparte Basin is made up of Cambrian – Cretaceous continental and marine sediments, Cambrian basic volcanics. The Ord Basin contains Middle Cambrian carbonates unconformably overlain by late Devonian marine sandstones. Victoria River Basin include Middle Proterozoic shallow to littoral (including carbonates) sediments overlain by shallow water glacial sediments. Whereas the Kimberley Basin has early Proterozoic shallow water sediments interbedded with volcanics intruded by sills, Shelf sediments including carbonates. The Halls Creek Origin has Early Proterozoic metamorphosed turbidite sequences with associated basic

volcanics intruded by basic dykes, sills and acid plutons which are overlain by acid volcanics (Palfreyman 1984).

The onshore geology of the northwest is shown in Figure 2.41. The main rivers cut through Cainozoic surficial sediments and deposit off shore river gravels, sand, silty clay, and clay (unpublished WMC report 1997). These are eroded from surface soils by sheet and rill erosion (Wasson et al. 2002), and rest on a palaeo-topographic surface of Proterozoic sedimentary rocks and Palaeozoic sedimentary and volcanic rocks (Palfreman 1984). Similar terrestrial-derived deposits on the NW side of the river mouths, noted by Lees (1992), result from the sediments of the Ord River catchment being deflected to the NW by the prevailing nearshore current regime. It is these coarse grained fluviially influenced deposits that have been targeted by several diamond mining companies (pers. comm..D. Skeen 2004). On the higher energy shoreline on the SW shore of Joseph Bonaparte Gulf, extensive sand-flats occur seaward of the high-tide zone and sandy barriers and beach ridges are spatially associated with fluvial inputs (pers. comm. D. Skeen 2004).

2.6.2 Sediment Yield

In north-western Australia, high erosion potential exists due to both the climactic regime and the nature of the rock-soil type and vegetation cover. The erosive nature of monsoonal rains impacting on light vegetation has yielded a significant sediment contribution to the marine environment. Recently this has combined with the land management practices of the pastoralists, loading the area with cattle, adding to the erosional nature of this landscape and thereby increasing the

sediment yield to the river system from 65 tonnes /km²/yr⁻¹ to ~100 t/km²/ yr⁻¹ (Harris, in Wasson 1995).

Throughout the Ord River Basin, the largest water quality challenge is sedimentation caused by sheet and rill erosion of surface soils. Loss of sediments from the catchment has consumed more than 10% of the original volume of Lake Argyle to date (WA Government 2003) and soil loss is greater than soil formation rates (Wasson et al. 1996). The Ord River Basin has an area of 47030km², the Ord Dam has a capacity of 10760 m³ x 10⁶ (WA Government 2003) with a 33.625 m³ x 10⁶ / yr⁻¹ infill rate over the past 32 years. This sediment would have otherwise been transported to the southern Bonaparte Basin for redistribution, close to shore, within the present day estuarine and marine environments.

Sediment yield for this area has been studied by the Public Works Department of WA (1969), Sadler (1970), Kata (1978), Wark (1987), Wasson (1994) and Wasson et al. (1996, 2002). Ambiguities in methods and resulting data for the work prior to 1987, downgrade their usefulness (Wasson 2002, pers com 2003). Therefore estimates by Wasson et al. (1996) are utilised for this study.

By using the pre-European sediment yield figure for the Lake Argyle dam, of 65t/km²/ yr⁻¹ (Wasson et al. 2002) and river catchment areas (88150 km², Appendix 2.5), establishing its overall volume of infill, and subsequently extrapolating this value for the Holocene (the past 11 ka), the total amount of fluvial derived sediment is established. This is total of ~63 x 10⁹ tonnes and a yet to be determined, percentage of this is deposited offshelf via the Penguin Deeps channel.

Tonnes / area / 11ka = tonnage throughout the Holocene.

Amount **65t (Wasson, 1994) X**

Area **88150 km² (WA Government 2003) X**

Time **11000 years (Holocene) = 63.027250 x 10⁹**

≈ 63 x 10⁹ tonnes of material

= 42.28 km³ volumetrically (assuming an excavated SG of 1.49).

No attempt was made to calculate either the amount of material contributed from the shelf environment over the Holocene, or aeolian material. Likewise, no attempt was made to adjust the calculations for the changing ‘total area’ as it varied throughout the Holocene in response to SL fluctuation.

On the basis of the above estimates, the Ord River Basin has contributed ≈18 x 10⁹ tonnes over the past 6000 years (65 tonnes X 47030 km² X 6 ka = 18 341 700 000 t). This volumetrically equals an excavated value of 12.06 km³.

The excavated rock expands by ~70% relative to *insitu* rock (Table 3.1 from Berkman 1995), so the excavated Specific Gravity (SG) of the material has been averaged and used for the sediment yield calculations.

Dry sand	SG 1.6	excavated	SG 1.28
Sandstone	SG 2.42	excavated	SG 1.38

Table 2.2 Specific gravities after Berkman, 1995

Chapter 2.7 Vegetation since the Last Glacial Maximum

2.7.1 Changes in vegetation distribution.

The Bonaparte Shelf shoreline, over geological time, has ranged from a precipitous shelf edge setting with deltaic deposition systems and saline restricted lagoon during the Last Glacial Maximum (LGM) (van Andel and Veevers 1967), to the tide-dominated estuaries and extensive mangrove fringes of the late Holocene and today. Catchment areas were much larger during the LGM, due to extensive shelf exposure (Figure 2.42) than those of the present day. The reduced in size as the rising sea level inundated the continental shelf up until the mid-Holocene.

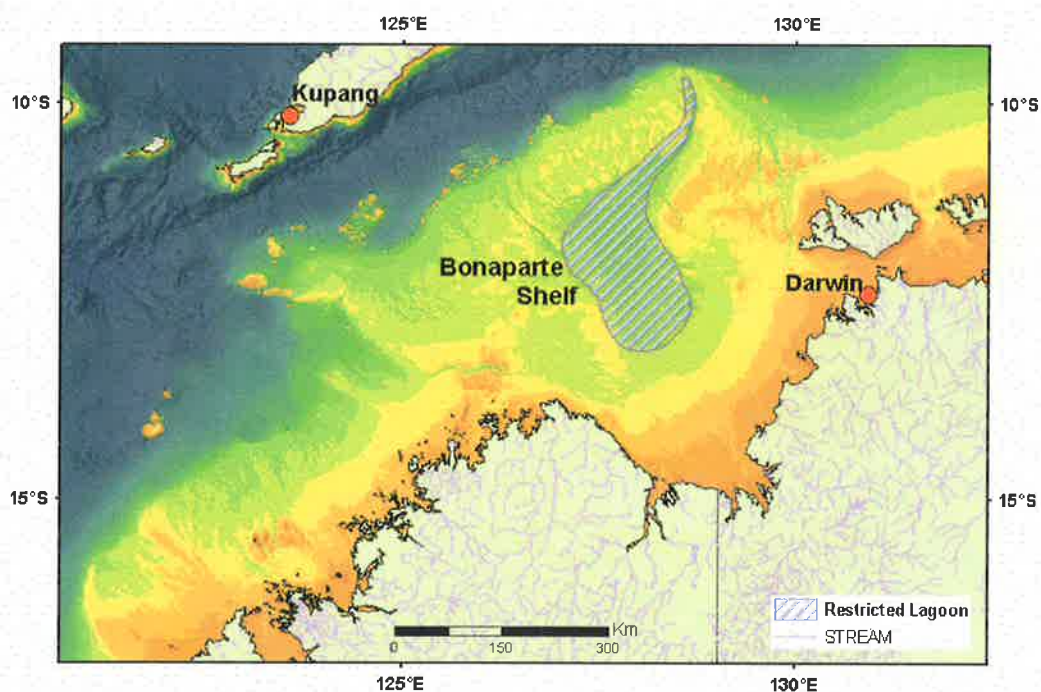


Figure 2.42 The present day drainage basins on the Australian continent contributing to the area of interest in the Bonaparte Shelf, and the location of the restricted lagoon during the LGM.

The restricted lagoon has provided other scientists (Yokoyama et al. 2001, de Deckker et al. 2002) researching environmental change and SL variation with both, key far-field and local core sites. This sites record these changes with both pollen and marine microfossils, the marine fluvial interplay during changes in SL.

Hantoro (1997) postulates that during the LGM, the onshore vegetation coverage for most of the Sahul Shelf was grass and shrub land with just the western tip of the Ashmore Platform and the northern edge of the Sahul Shelf covered by open forest woodland (Figure 2.43).

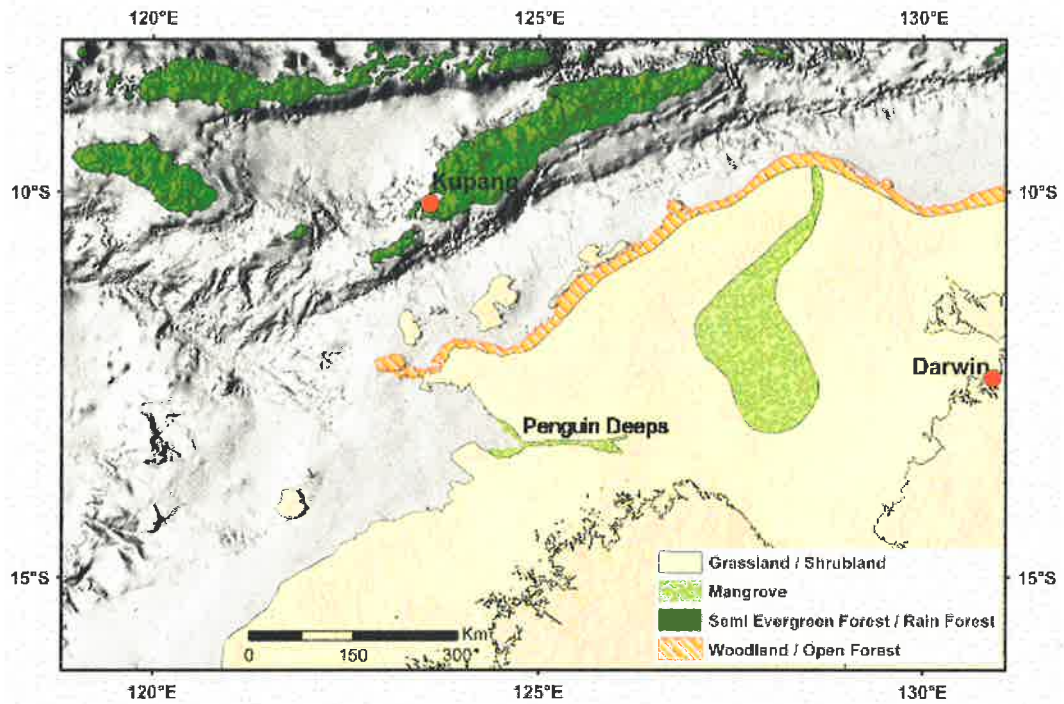


Figure 2.43 Vegetation of the LGM, extending Hantoro's work (1997) across the study area. The horizontally orientated Penguin Deeps and adjacent mid shelf environments are sites of transitional mangrove vegetation during LGM.

Today vegetation on the modern onshore Ord Basin includes short grass and low tree savanna on stony rises, covers most of the basalt areas and also the plains (these plains are developed over the top of sandstone). Spinifex and light tree cover occurs over limestone outcrops, and short grass savanna covers shaly areas. The onshore Bonaparte Basin is covered by moderately dense high grass savannah woodland and spinifex on rocky hills (Mory and Beere 1988).

Riverside (riparian strips) vegetation also varies according to the influence of the flooding regime and substrate type (Pettit et al. 2001). Estuarine environments

have salt resistant vegetation, including mangroves, grasslands or herb-lands. This vegetation provides critical habitat for a diverse distinctive bird fauna (Johnstone1990) and yield distinct palynological environmental indicators.

In summary, there has been significant change of the terrestrial flora since the LGM, with the onset of a rising sea level. This sea level rise of ~124m (Yokoyama et al. 2001) on the generally low relief shelf reclaimed much of the Bonaparte Shelf. During the LGM, the vegetation would be similar to the present day onshore Ord Basin with exception of the areas immediately adjacent to the palaeo river courses and areas of the Bonaparte depression restricted marine lagoon (Figure 2.43). These areas had vast mangrove areas and more extensive riparian vegetation tracks.

Chapter 3. Surface morphology and surficial sediments of the study area.

3.1 Surface Morphology

The Bonaparte Shelf, is situated on the north western Australian continental margin (Figure 3.1) covering an area of ~315 000 km² with shelf edge depths ranging from 70 – 165m and the Sahul Shelf comprises the north western flank of the Bonaparte Shelf. The continental shelf rises from the Argo Abyssal Plain in the west, and the Scott Plateau, Browse Basin to the south west. The southern edge is bounded by the Kimberley Shelf, Leveque Platform and the Kimberley Block. It is bordered by the Money Shoal Platform and the Timor Trough to the northwest and north respectively (Figure 3.1).

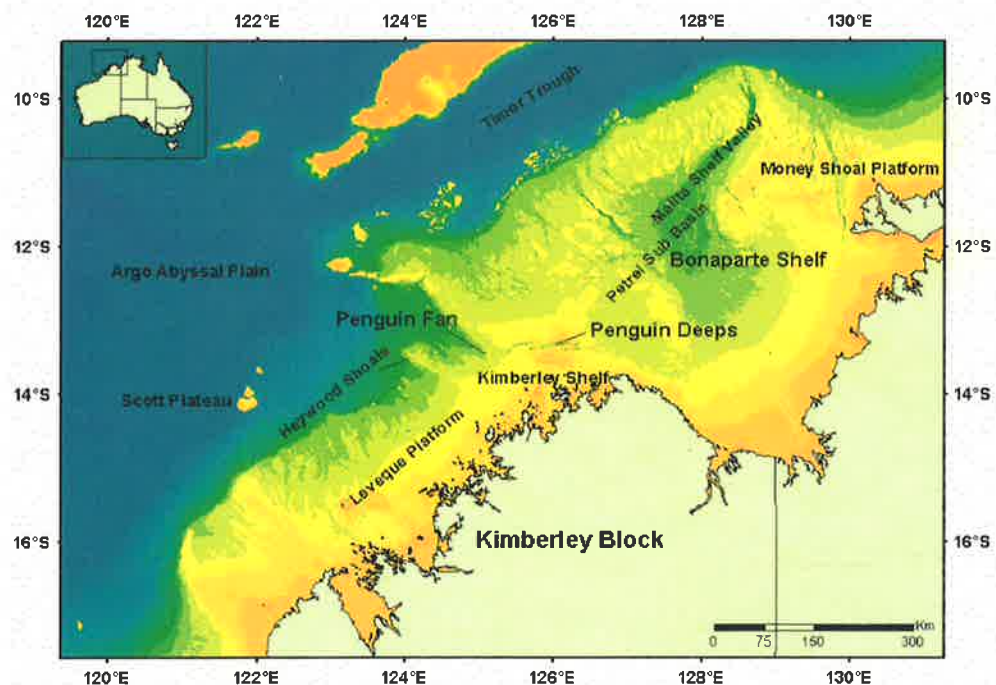


Figure 3.1. The regional bathymetry Australia's Northwest Shelf.

The Bonaparte Shelf has a central depression, the Bonaparte Depression and the outer edge of the shelf is ringed by a range of channels incised to depths up to 165m. These vary in length from 10 – 200 km and are up to 8 km wide. Whilst the majority are open ended some of the channels are 'blind' at each end

(Marshall 1994). These channels radiating to the north and west, are incised into older underlying Pliocene / Pleistocene sediments (van Andel and Veevers 1967; van de Kaars 1991) and focus the flow of marine waters across and off the shelf. A series of biogenic terraces and flat topped banks (van Andel and Veevers 1967) are located at the shelf edge.

Two dominant drainage features occur on the shelf. The larger is a sinuous channel that crosses the shelf to the north from the central depression, along the Malita Shelf Valley (Figure 3.1). The second conduit, the Penguin Deeps (Figure 3.2, 3.3, 3.4 a, b) is found at the south-western edge of the Bonaparte Shelf, a region of significant topographic variation. Both industry seismic and the sub bottom profiles from this study indicate that the Penguin Deeps is not obviously structurally controlled, *per se*, at the regional scale where it enters the Timor Sea / Indian Ocean. The Penguin Deeps run east-west, terminating in 70—300 meters of water, where sediment deposition has formed a submerged sediment fan approximately 100 km long and up to 75 km wide on the western most end (Figure 3.2). This fan and the Browse sea valley are bound by two positive topographic features. The first, to the south, is Heywood Shoals and its associated ridge trending NW / SE to the south, and the second, a shelf break, parallel to the regional Browse - Bonaparte transition zone to the north, which also trends NW / SE (Figure 3.2).

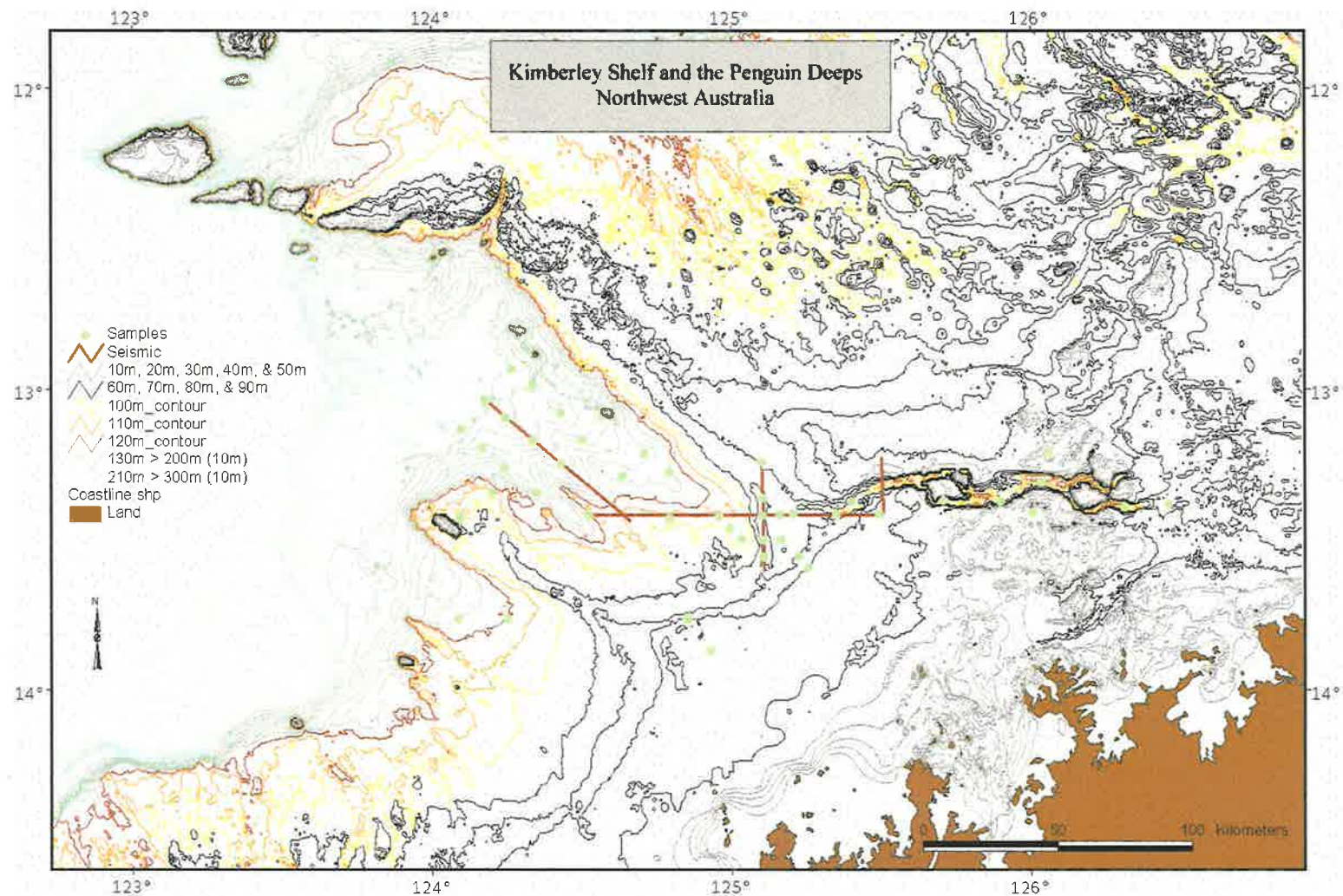


Figure 3.2 The Kimberley Shelf and the Penguin Deeps seismic, gravity core and sediment sample sites with contour map.

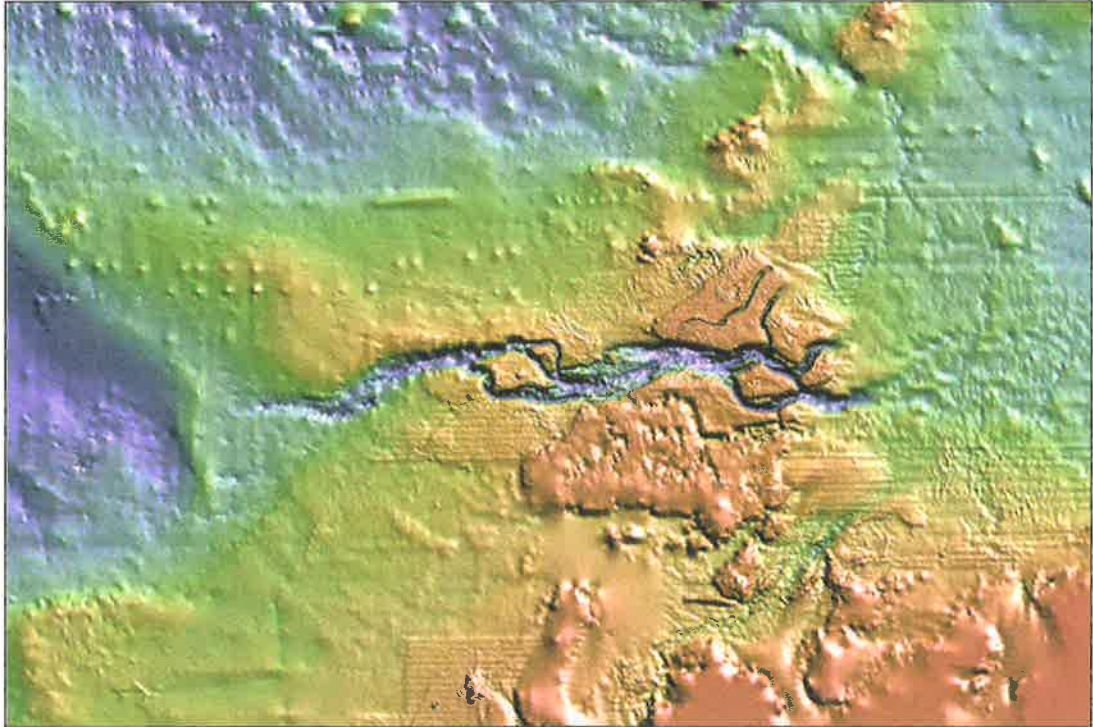


Figure 3.3 A plan view of the linear drainage feature, the 'Penguin Deeps' ~150 km in length and up to 8km wide.

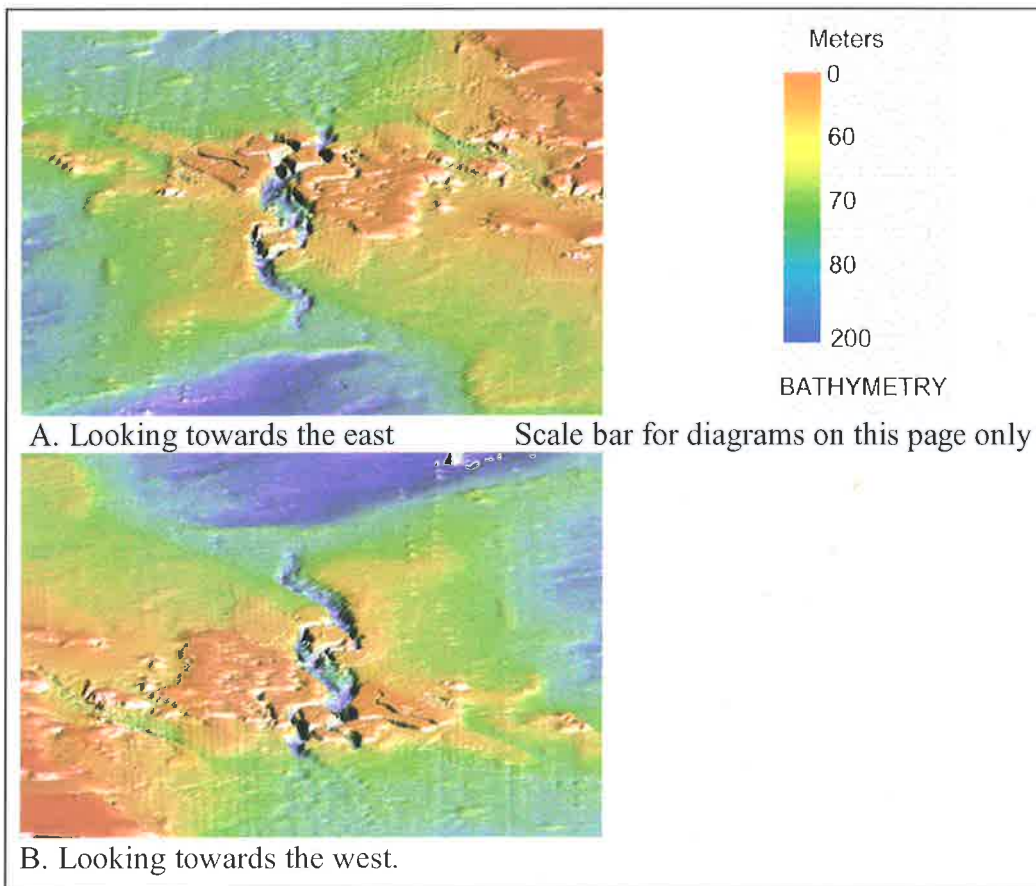


Figure 3.4 The Penguin Fan. A, viewing from the west up onto the Kimberley Shelf from the Browse Sea Valley. B, Viewing from the east from the Joseph Bonaparte Gulf / Kimberley Shelf out towards the Browse Sea Valley.

3.2 Previous work

Several carbonate bioherms, including emergent platform reefs, pinnacle reefs, shoals, and submerged banks (Figure 3.5), occur along the shelf break and along the Browse-Bonaparte Basin transition zone. These submerged banks are typically steep sided ($15 - 20^\circ$) rise from water depths of $> 150\text{m}$, and grow to within 20 m of the sea surface (Marshall et al. 1993; Heyward et al. 1997). The modern emergent reefs are built on relatively tectonically stable antecedent topography (Yokoyama et al. 2001). Additionally some of the carbonate banks and shoals that make up the Sahul Shoals, lie on the edge of an ill-defined Pliocene / Pleistocene fossil reef chain (Figure 3.5), (Teichert and Fairbridge 1948; Fairbridge 1950; Edgerley 1974).

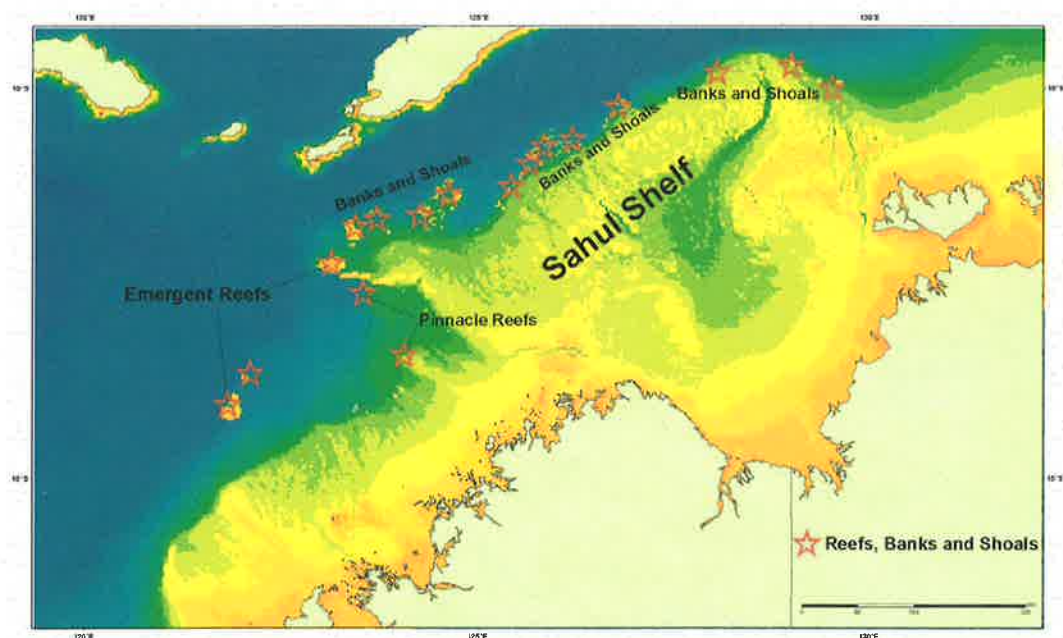


Figure 3.5 Reefs, banks and shoals of the Sahul Shelf, along the northwest Australian continental shelf edge.

Fairbridge (1953) was the first to offer a regional picture of the sediment facies describing a pattern which related, first, to the distance from shoreline, and, second, to distance from reefs or shoals. A coarse grained shelly or coralline sand with abundant ironstone fragments occurs around shoals and pass laterally into a

calcareous sand on the open shelf surface, and a terrigenous sand nearshore. Away from the terrigenous influence of the shoreline, or the coarse sediments associated with shoals, the middle and outer shelf is covered by a blanket of green (glauconitic) sandy mud across the shelf edge and upper slope, this mud interestingly contains more abundant planktonic foraminifera offshore and passes into *Globigerina* ooze at depths greater than ~2000 m.

Fairbridge's summary was confirmed and extended by van Andel (1965), van Andel and Veevers (1967) and van Andel et al. (1967), who made a comprehensive study of the regional sediment distribution on the Bonaparte Shelf (Figure 3.6, 3.7), and by Lees (1992), who provided a detailed account of an inshore (terrigenous) area in the southeast corner of the Bonaparte Gulf, adjacent to the mouths of the Pentecost and Victoria Rivers. These studies combined with observations and analyses from this present study have given rise to a regional sediment textural map (Figure 3.8)

While the closest sample from this study was taken 60km offshore, Clarke et al. (2000, 2001) and others, worked closer to the modern shore line and found areas of high concentrations of quartz, which physically indicate the presence of former littoral zones during temporary standstills in the Holocene marine transgression (Clarke et al. 2000, 2001). The work by van Andel and Veevers (1967) also shows a wider distribution of terrigenous sourced sediments towards the Bonaparte Depression (Figure 3.7). Today, much of the inshore biogenic material is reworked older material and this may mask the quantity of modern terrestrial fluvial inputs (Lees 1992).

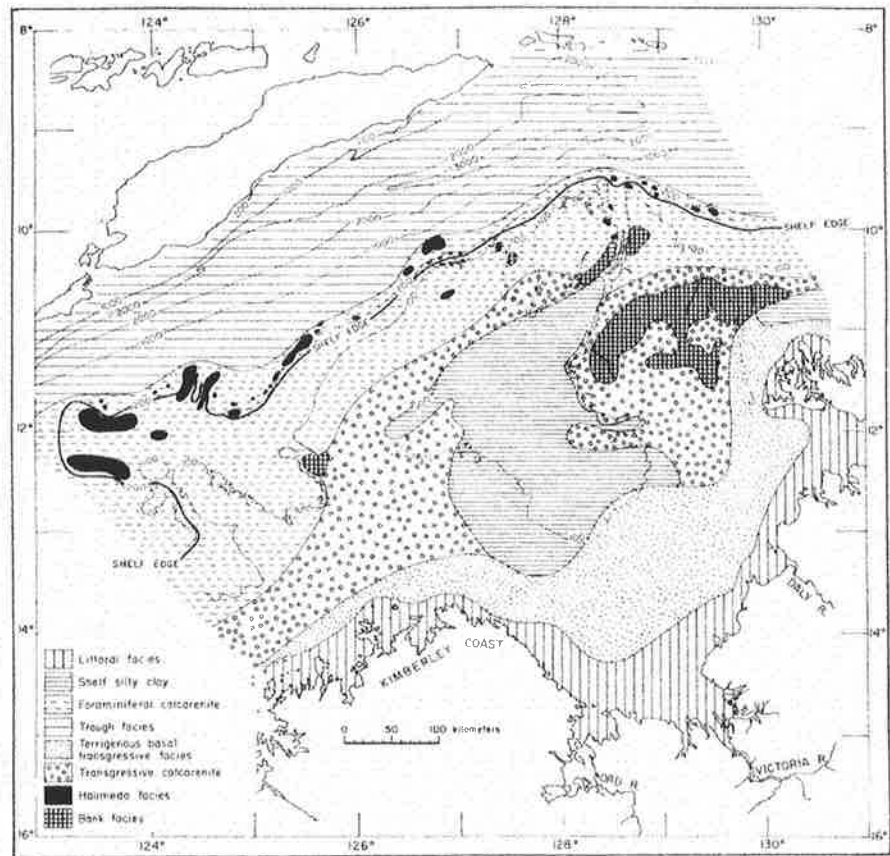


Figure 3.6 Sediment textural map of the Bonaparte Shelf (van Andel, 1965)

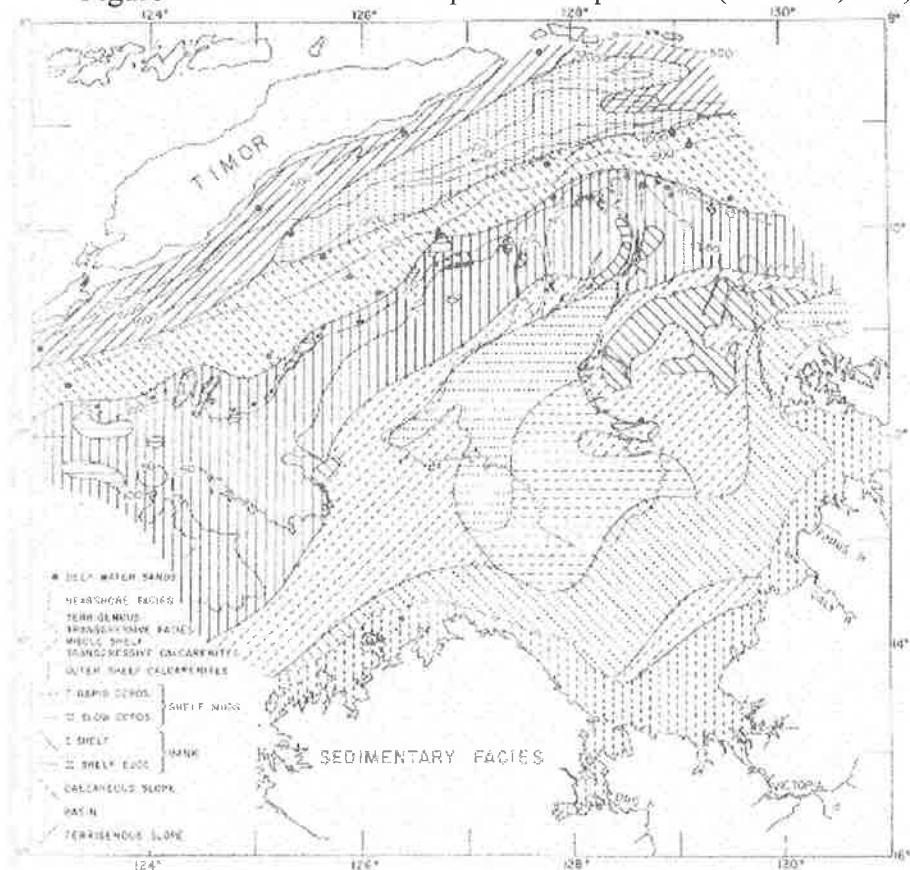


Figure 3.7 A regional appraisal of the sedimentary facies by van Andel and Veevers, 1967.

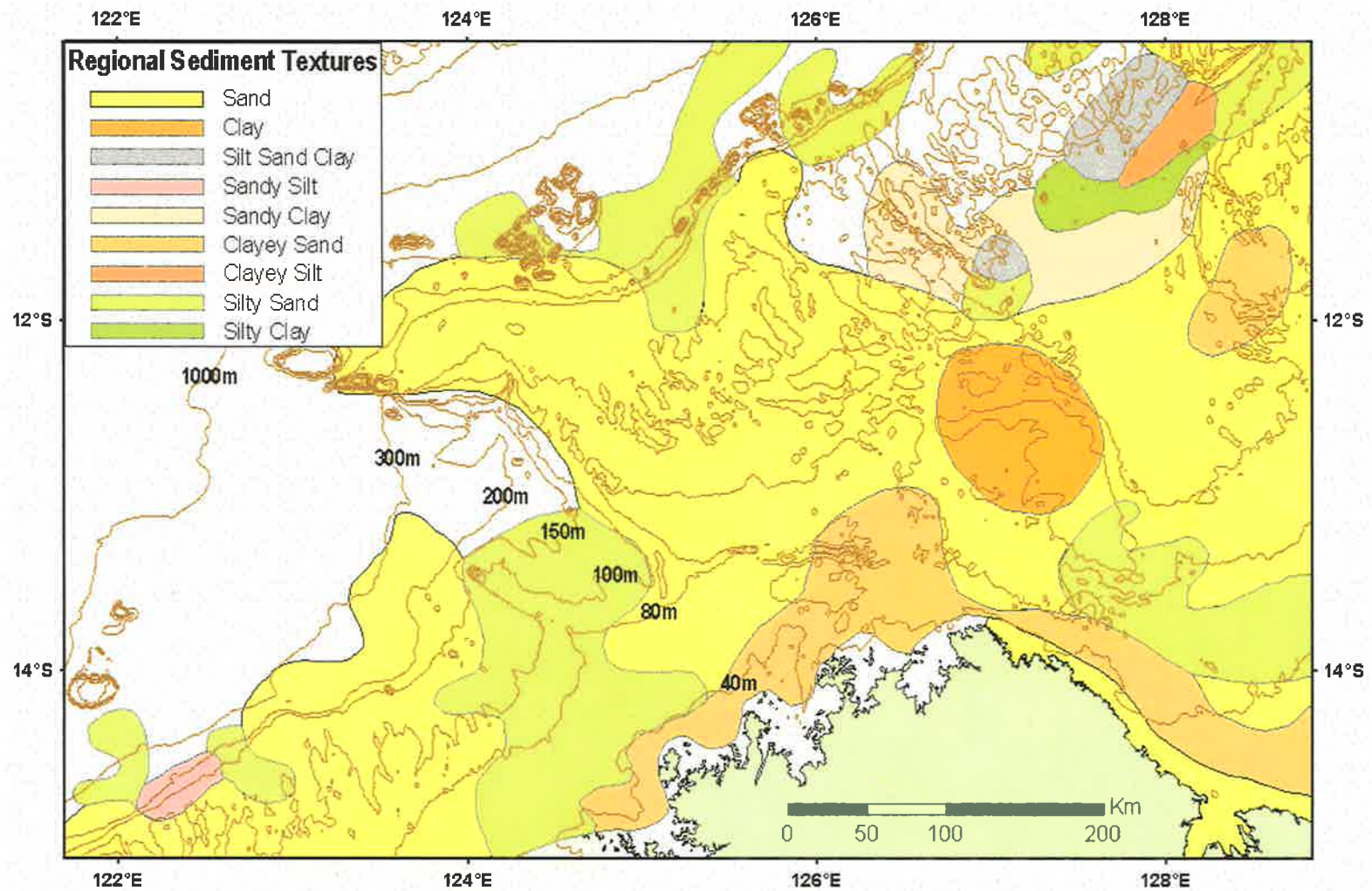


Figure 3.8 Regional sediment textures combined data sets from previous studies and present study.

Sediment deposits are generally thin (van Andel and Veevers 1967); the highest sediment contributor across the shelf, in present conditions, is biogenic carbonate. The transported and *in-situ* biogenic sediments contain a range of bryozoans, molluscs, ostracods, coralline algae, branching corals and foraminifera with minor percentages of solitary corals, echinoids, soft coral and sponge spicules with the muds containing comminuted biogenic carbonates and in some examples, terrestrially sourced silts and clays (van Andel and Veevers 1967, Clarke et al 2000, 2001).

At times of sea level lowstand, the exposed shelf was subject to surface weathering and erosional regimes forming drainage patterns across and into the large epicontinental embayment of the Bonaparte Gulf (Clarke 2000, 2001) and to a lesser extent towards the Penguin Deep. During the LGM, the Bonaparte Depression contained a well developed, restricted marine lagoonal in its centre and through the work by van Andel and Veevers (1967) a broad understanding of the facies (3.6) and texture (3.7).

Throughout the Holocene, the sediments being transported along and off the shelf contain both fluvial-derived material and modern biogenic carbonates from the shelf (Clarke et al. 2000). This mixture of sediments today occurs close to the coastline whereas the reworked shelfal carbonates, Pleistocene in age (Clarke et al. 2000) and modern biogenic carbonates, have a larger, shelf-wide distribution (Figure 3.8).

3.3 Regional sediment facies of the Sahul Shelf

3.3.1 The shaved shelf

Spatially, the Bonaparte Shelf is capped by one of the largest discrete areas of continental shelf in the world. It is described by Harris et al. (1994) as a 'shaved shelf'. This term, first coined by James et al. (1994), indicates that the rate of sediment erosion is close or equal to the rate of production / accumulation. This description is confirmed by this study. Clarke et al. (2001) found that the sediments that are accumulating on the inner shelf, close to the modern shoreline, contain a heterozoan assemblage that appears to be governed more by turbidity than by temperature. The sediments of this present study, across the Kimberley Shelf and Browse Sea Valley concurs with the observations of the sediments identified by Clarke (2001) in adjacent environments as they included a range of bryozoans, gastropods, echinoderms, solitary corals, benthic and to a lesser degree planktic foraminifera.

The seabed morphology of the Sahul Shelf, Penguin Deeps and Browse Sea-valley (Figure 1.1) reflects the interaction of basement tectonics, Quaternary sea-level fluctuation, terrigenous sediment supply from continental Australia, and marine biogenic (calcareous) sediment supply. The location of areas of Holocene sediment deposition and sublevation is controlled largely by two hydrographic effects (a) tidal current streams, especially around coastal inlets and reefs or shoals and (b) cyclone-induced currents, especially on the open, shallow shelf.

The shore-connected prism of terrigenous sand and mud described by Lees (1992) occurs on the inner shelf throughout the southeastern portion of the Joseph Bonaparte Gulf and also along the inshore Kimberley Shelf further to the west and south. This inshore sediment prism (ISP; cf. Larcombe and Carter, 2004) is elongated parallel to the coastline and contains increasing admixtures of marine carbonate material offshore. The sediment is mostly carbonate-rich (>80%) between ~20 m depth and the shelf break, variably muddy or sandy, and has a detailed distribution which closely corresponds to the bathymetry, with finer grain sizes occurring within the Bonaparte Depression and other parts of the offshore shelf, and coarser biogenic sands and gravels distributed across bank tops, terraces and the general shelf surface. Sediment on the shallower mid-shelf contains abundant reworked pedogenic material (Fe-stained carbonate pellets) and common glauconite and glauconitized shells, together with fresh (modern) bioclasts with planktic foraminifera increasing seawards, indicating a palimpsest origin and a slow modern accumulation of mixed biopelagic / biobenthic material. The sediments contain increasing amounts of terrigenous silt (>~50 m) and clay (>~250 m) outboard with increasing depth across the outer shelf and slope.

3.4 Sediments

3.4.1 Setting: Energy levels

Sediment grain size can give an indication of the energy level during deposition. Higher energy levels remove the fine fractions, leaving the larger fraction to accumulate. On the other hand, insitu production of coarse grained particles can be misleading (James and Kendall 1992). This includes a wide range of predominately benthic invertebrates, eg. benthic foraminifera, solitary corals,

byozoans and planktic contributions from both foraminifera and pteropods. Thus, lower energy levels are incapable of moving large grains and therefore can be dominated by fine sediment. In an active bioturbated substrate, such as many of the sediment core sites within the study area, mollusc, arthropod and annelid burrowing have redistributed and mixed sediments down core. If the large benthic foraminifera, vagrant bryozoans and solitary corals remain within the sample during processing, they skew the sediment analysis, as their size does not reflect the depositional energy, but rather indicates a favourable habitat.

3.4.2 Preservation of Skeletal Components

The state of preservation of skeletal components can give an indication of their relative age, especially when variation occurs within one bioclast type (Radke 2000). The potential for inorganic staining, internal precipitation of glauconite, fragmentation, micro-boring and encrustation increase with time, and a predominance of any of these types of alterations, tends to be environmentally specific. Yet as all samples in this study come from the same region and have been subject to similar erosional and depositional regimes, the results of the physical and geochemical analysis have been viewed in direct comparison.

The alteration of the sediments occurs via three different modes, physical chemical and biological.

Physical; (a) Breaking of the material from the production site e.g. the attachment processes of corals and fenestrate bryozoans can be broken off during storms, by internal waves or by current energy, (b) transport derived abrasion of individual sediment grains as the material saltates along the sea floor, (c) infilling of pore

spaces with finer grained sediment affecting the weight of the sediment and subsequent changes in its hydro-dynamic qualities, (d) collision damage.

Chemical; (a) exposure at times of lower sea level allows for faster oxidation and solar damage, (b) sediment grains offer a nuclei for the chemical precipitation of calcium carbonate, (c) the full range of early sea floor and / or subaerial exposure diagenetic processes, infilling of fossils including iron oxides and hydroxides of sub areal origin and glaucony and pyrite of submarine origin.

Biological; (a) boring of the sediment grain by biota including gastropods, annelids, sponges and rasping fish, (b) encrustation by other biota eg bryozoans, sponges, calcareous algae and surpulids, (c) Ingesting of sediments during feeding by echinoids and holothurians.

The distribution of shelf sediments is strongly influenced by production rates, production sites, sediment transport regimes, accumulation zones / depo-centres and sea level change over time as seen on the Bonaparte Shelf (Figure 3.9 a, b).

These factors are also greatly influenced by climate variation and by the bathymetry, slope and aspect of the sea floor (Figures 3.10, 3.11, 3.12). The enhanced sub-aerial erosion potential of the Bonaparte platform and the location of depo-centres at times of lower sea level, were both different to today (Figure 3.9. a, b). This is due to a broader shelf area, the onset of the monsoonal system (Wyroll et al. 2001) the subsequent higher erosion rates (pers. comm. R. Wasson, 2003) and available depositional / accommodation space. The off-shore transported terrestrial sediment today are deposited along the north east and north facing coast of the southern Bonaparte Gulf (Clarke et al. 2000, 2001), whereas

during lower sea level they were transported further across and off the shelf and deposited in the channels and down the shelf slope.

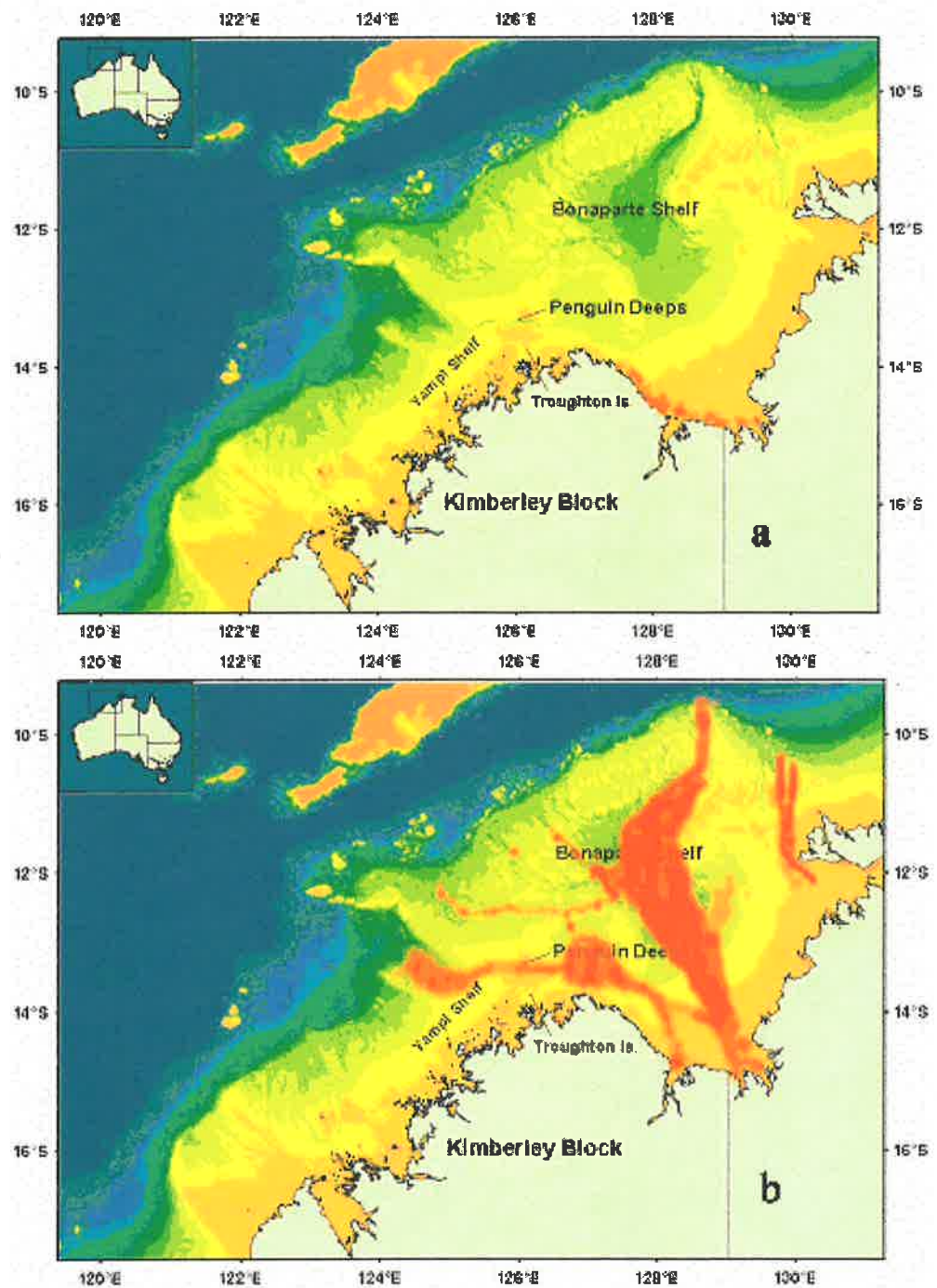


Figure 3.9. Regional deposition centres today (in red) for terrestrial sourced sediments (a) and proposed areas during the last Glacial Maximum (b) from this study.

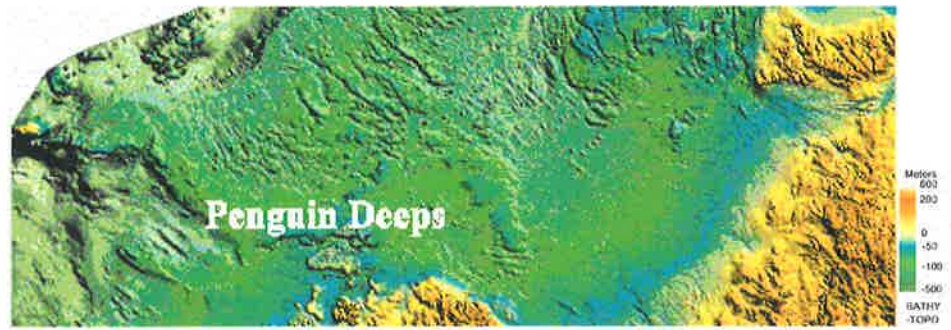


Figure 3.10 Bathymetry of the Bonaparte Basin (Non projected image).



Figure 3.11 Slope in degrees of the Bonaparte Basin (non projected image)



Figure 3.12 Aspect of the Bonaparte Basin (Non projected image)
Ship tracks and horizontally linear computer artefacts are evident in these three diagrams.

3.5 Introduction to the surficial sediments of this study.

A series of 95 sediment samples from surficial sediments and sediment cores were utilised for analysis (Figure 3.2, appendix 3.1). Sediments were subjected to an initial imaging process, grain size, CaCO_3 percentage, Total Organic Carbon analysis, and a subgroup of these were selected for AMS Carbon dating (Table 3.1).

3.5.1 Methods; Laboratory Sampling Protocol

3.5.1.1 Digital Imagery

The sediment sample was photographed digitally in colour immediately after removal from cold storage, and then appraised for any anisotropy of fabric that may have been either inherent in the sediment, or developed in transit to the laboratory. Any large biota were noted.

Representative views of the sediment were photographed at the lowest magnification possible so that individual particles remained identifiable. Unusual bioclastic components were also photographed for future work. Dried and processed sediment was imaged for descriptive appraisal (Chapter 3.5.1.7)

3.5.1.2 Colour

The colour of the sediment sample was determined by direct comparison with colour charts (Munsell, 2000). Where the colour was strongly variegated, the extreme hues were recorded. Where there was lesser colour variation, the average hue was determined on the blurred image when the sample was moved to and fro.

3.5.1.3 Sub-Sampling

Loose sediment samples were heaped into a cone and quartered. When the sample was still too large it was again bisected, normal to any observed textural variation. The sample weight necessary for a representative sample was determined. In this study, sample weights were standardised at 50 grams.

A representative thin sliver of sediment of approximately 20 grams was taken from across this central cut. This smaller sample was designated for bulk analyses such as chemical, mineralogical, TOC, TIC, Total CaCO_3 . Salts were removed from the sediment by repeated washing in distilled water, allowing the sediment to settle, decanting the supernatant, and repeating the procedure several times before drying at 40°C , crushing and powdering.

Two sub-samples of approximately 50 grams were cut as representative segments from the mirror faces of the remaining sediment.

- a) Sample for description.
- b) Sample for analysis of size fractions

Any remaining sample was reduced to about 200 grams, repackaged and returned to cold store as an archive sample.

3.5.1.4. Sediment Description

Sand and gravel fractions were examined using the same descriptive Geoscience Australia protocol as outlined in the observational datasheet (Appendix 3.2). Additional observations were taken at time of acquisition and are included in Appendix 3.3.

3.5.1.5 Microscopic Examination

Following standard Geoscience Australia protocols, a Leitz MZ12 stereozoom microscope was used with a side-mounted Olympus DP11 digital camera.

The abundance of the various bioclast types were estimated visually by volume percent. Such an appraisal is challenging because of the variable size, shape and density of particles and consequently errors margins are to be expected. Re-sampling of 12% of the samples indicated that estimation errors of 10% are probable. The abundance of major components were demanding to estimate, especially when more than two dominant types were present in the sample. There was a tendency towards overestimation of minor components. However, because only one observer was involved, it is likely that estimation biases are consistent throughout this study.

3.5.1.6 Recording observations

Specific features of preservation are recorded in an abbreviated notation that follows Geoscience Australia protocols, an abbreviation key for which is included in the sample data sheet (Table 1). This abbreviation key is also included as a sheet on the Excel sediment file.

3.5.1.7 Descriptions.

Estimation of modern and relict components of sediment also adhered to Geoscience Australia protocols formed by B. Radke (2002). Preservation of the skeletal components gives an indication of their comparative age, especially where there is variation within the one bioclast type. An expected order of change with time might include disarticulation of the skeleton, and devitrification of the surface of the bioclast. The probability of inorganic staining increases with time as does the precipitation of glauconite internally within tests. Fragmentation, micro-boring and encrustation should also increase with time. Clearly, all features of bioclast preservation need to be considered collectively as each type of bioclast is prone to degradation at different rates. The cumulative alteration of a bioclast is profoundly dependent on the mechanical abrasive energy in the ecosystem, and the influence of encrusting and micro-boring biota. An additional complication is that features of ageing may be variably erased by the mechanical abrasion.

Despite these cumulative uncertainties, an attempt is made to categorise bioclasts on the basis of age — fresh, intermediate and relict. Having separated the sand gravel and mud fraction of the surficial samples, the samples were then again grouped in to three further categories.

1. Fresh sediments. These are biogenic sediments that have little or no evidence of transport, exposure/staining, reworking or degradation.

Generally thought to be Holocene in age in this locality. Fresh components tend to retain vitreous surfaces, but may or may not remain articulated.

2. Intermediate sediments. These sediments show distinct evidence of staining and in many samples bio-degradation and transport. Using observational skills only the samples are generally thought to be Pleistocene in age.
3. Relict sediments. These bioclasts generally have major modification by mechanical abrasion, alteration to the microstructure, micro-boring and bioerosion, and/or inorganic staining. They are generally stained, rounded, abraded and at times in-filled with glauconite. Using observational skills only, the samples are generally thought to be Pliocene / Pleistocene or older in age.

The degree of fragmentation is not generally a consideration because, as well as the period of exposure of the bioclast, both mechanical abrasion and bioerosion in the system can be variable. The extreme result of these processes is generally a nondescript carbonate particle of indeterminate origin that is macroscopically indistinguishable from carbonate intraclasts. Many intermediate stages and combinations occur between these extremes of preservation, where even relative age is difficult to estimate. Consequently only the modern and relict categories are reliable.

3.4.1.8 Carbonate percentage analysis

The Carbonate percentage analysis method was the Geoscience Australia SOP, # SED-2003-1.0 (Watson, Ramsay and McLachlan. 2003)

3.5.1.9 Grain size analysis

The grain size analysis was undertaken using the Geoscience Australia SOP for the Malvern Laser Particle Size (grainsize) Analyser. # PMD-SED-SOP-2 (Watson, Ramsay and McLachlan 2003)

3.5.1.10 Accelerator mass spectrometry dating

Accelerator mass spectrometry (AMS) was undertaken using the following method; Pre-treatment included examination of samples under a microscope. Obvious extraneous materials are picked out with forceps. Surface dirt and contamination is removed. The samples were then cleaned using ultrasound. Upon completion there were sent to Rafter Laboratories for processing.

Processing is per SOP at Rafter Laboratories.

(<http://www.gns.cri.nz/rafter/rafter.htm>)

3.5.1.11 Carbon and oxygen isotope analysis

The sediment samples are prepared for the isotope analysis the using the following method.

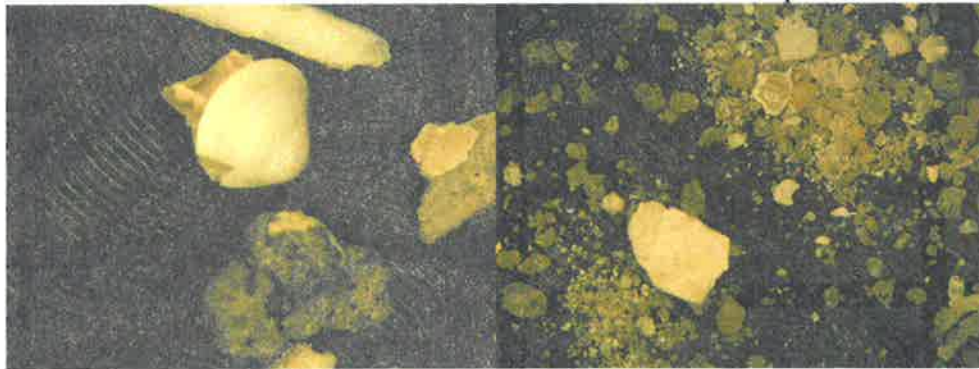
Initially the samples were dried at 50⁰C then homogenised by crushing to a fine powder in a tungsten ring mill. Sub-samples were reacted with 5% hydrogen peroxide until the end of visible gas generation to remove organic carbon compounds. This required repeated stirring and in some cases decanting the supernatant and refilling with fresh hydrogen peroxide solution. Sub-samples were dried again (50⁰C) before analysis.

Carbonate isotope samples were analysed via an automated on-line “Micromass Isocarb” device that reacts samples with 100% orthophosphoric acid in a common acid bath. The gas generated passes through two water traps before being analysed by a dual-inlet Micromass Optima mass spectrometer. Each analytical run of 40 samples contained two international NBS19 standards ($\delta^{13}\text{CPDB} = 1.95\text{‰}$; $\delta^{18}\text{OPDB} = -2.2\text{‰}$), five internal bicarbonate standards, and five blanks for calibration and accuracy. The blanks are used to detect any potential memory effects, cross contamination between samples, or machine drift through the run. Analysis was performed under the guidance of Dr. P. Gammon, Department of Geology and Geophysics, Adelaide University.

3.6 Images and descriptions of the Kimberley Shelf surficial sediments.

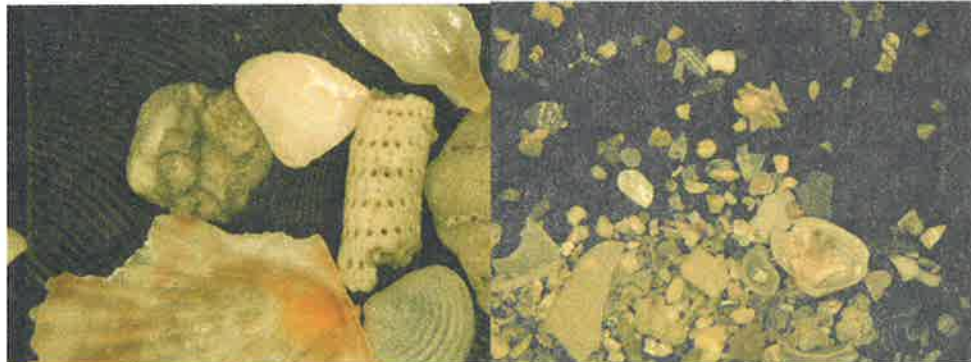
All surficial sediment samples have been sorted for grain size and imaged. Images here are of both the gravel and sand size components and are imaged at the same scale of X 3.7. The image on the left hand side depicts the gravel fraction, and the right hand side image is the sand fraction. The frame of the image is ~12 mm in width.

Sample 6401603 #1



Large relict grains, bivalves and biogenic fragments make up the gravel fraction and the sand fraction consists of pteropod fragments, and a range of broken bioclasts.

Sample 6401604 #2

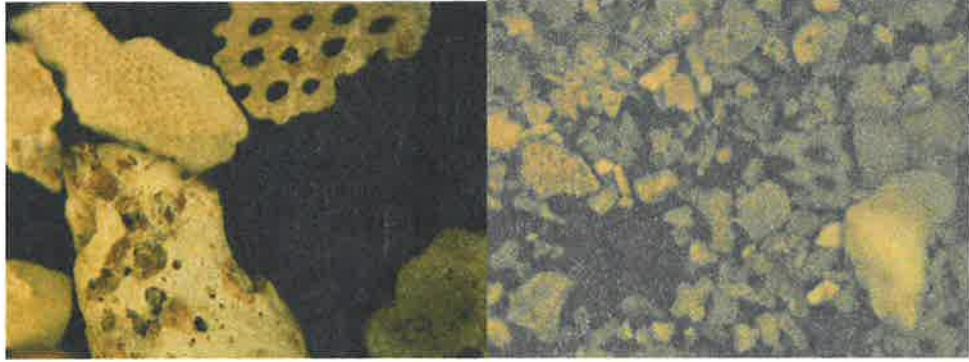


Bilvalves pteropods and coralline fragments of different ages make up the gravel fraction (LHS) and the sand fraction (RHS) contains ostracod tests, sponge spicules bivalve fragments and a wide range of bioclasts.

Scale = 1 cm

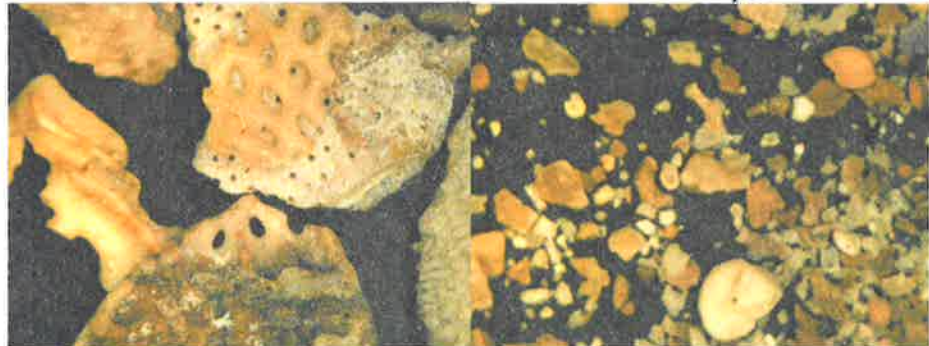


Sample 6401605 #3



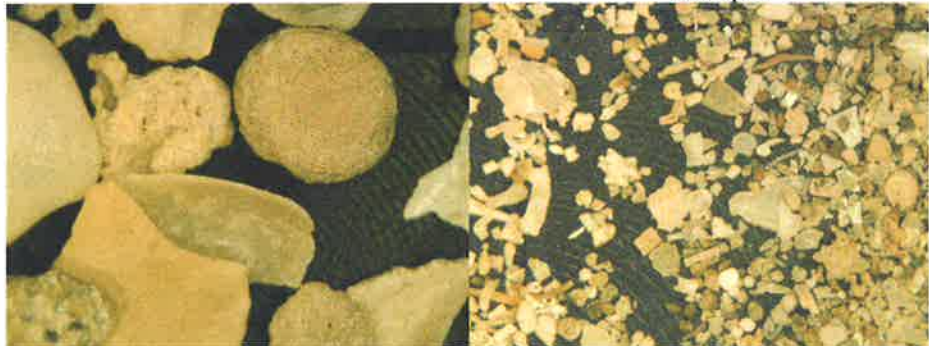
Relict fenestrate and coralline algae encrusted bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) contains fenestrate bryozoans, sponge spicules bivalve fragments and a wide range of bioclasts.

Sample 6401608 #6



Stained fenestrate and branching bryozoans, stained large encrusted bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) heavily stained orange indicating exposure, contains small bivalve fragments and a wide range of bioclasts.

Sample 6401609 #7



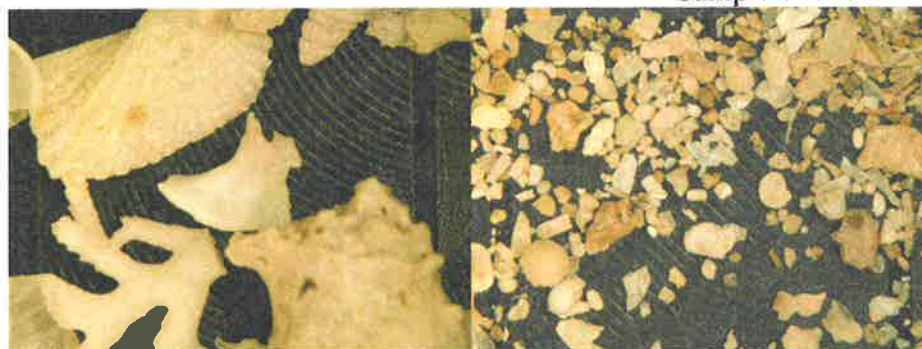
Large fragments of bivalves, benthic foraminifera and assorted bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) contains bivalve and bivalve fragments, ostracods, pteropod fragments, benthic foraminifera and bioclast hash.

Sample 6401610 #8



Large fragments of bivalves, fenestrate bryozoans and assorted stained angular bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) contains bivalve and bivalve fragments, gastropod fragments, benthic foraminifera and fenestrate bryozoans.

Sample 6401611 #9



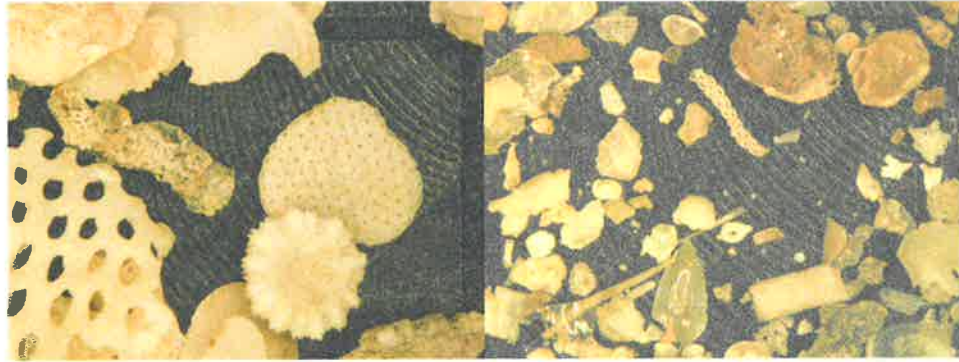
Large fragments of bivalves, fenestrate bryozoans and assorted stained angular bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) contains bivalve and bivalve fragments, gastropod fragments, benthic foraminifera and fenestrate bryozoans.

Sample 6401613 #11



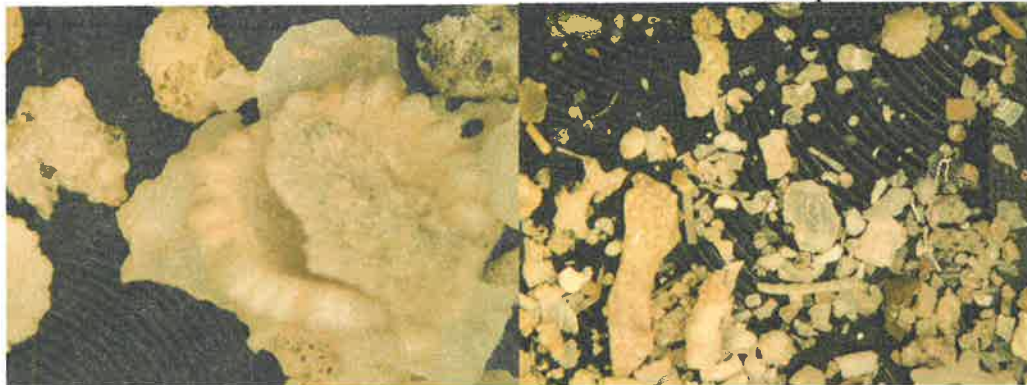
Large fragments of surpolid encrusted branching bryozoa, bivalves, and assorted heavily stained angular highly porous bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) contains angular bivalve and bivalve fragments, benthic foraminifera and assorted stained and in some cases polished corallgal bioclasts.

Sample 6401614 #12



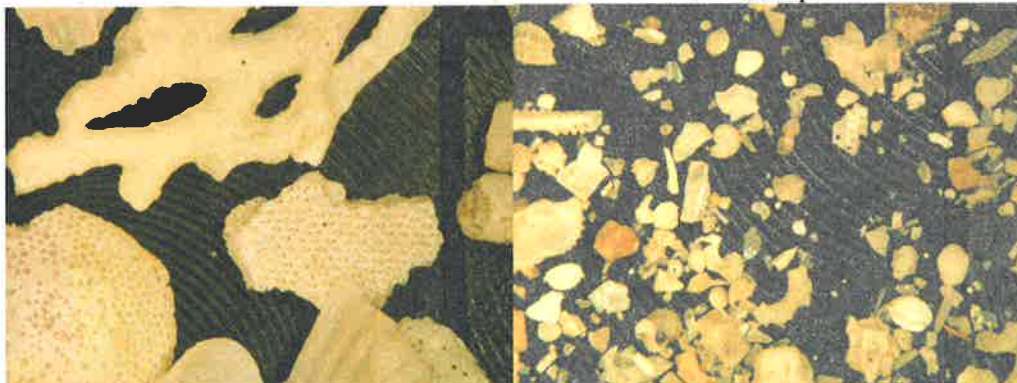
Fenestrate and vagrant bryozoans, stained large encrusted bioclasts make up the gravel fraction (LHS) and the sand fraction (RHS) heavily stained orange indicating exposure, contains small bivalve fragments and a wide range of bioclasts including benthic foraminifera, fenestrate bryozoans pteropods fragments.

Sample 6401615 #13



Large vagrant bryozoans encrusted bioclasts some with internal staining perhaps glauconite. The sand percentage on the LHS contains branching bryozoans pteropods fragments, small gastropods both benthic and planktic foraminifera and an angular biogenic hash.

Sample 6401616 #14



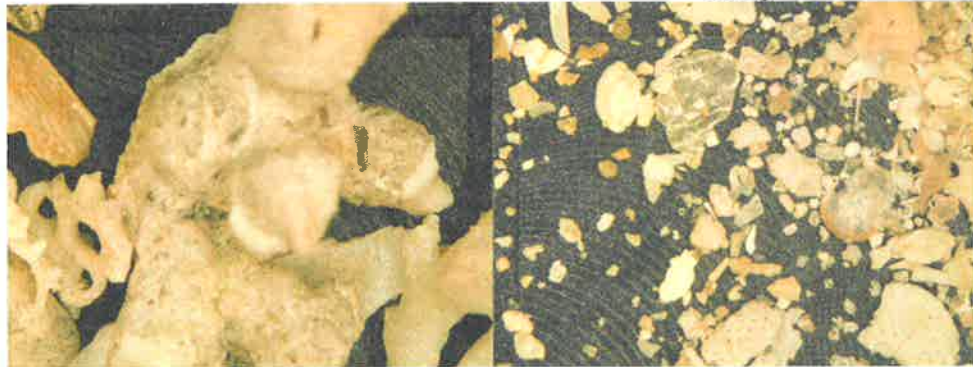
Large fenestrate bryozoans and solitary corals dominate the gavel fraction, with bivalve fragments and robust thick benthic foraminifera. The sand percentage contains a range of stained, non-stained and bioclasts with gastropods, benthic foraminifera, bivalves pteropods fragments.

Sample 6401617 #15



Fresh pteropods bivalves, coupled with encrusted fenestrate Bryozoans and assorted surpulid encrusted bioclasts make up the gravel fraction. The sand percentage contains both angular and rounded sediments containing benthic foraminifera including agglutinated forms, gastropods and angular mollusc fragments, some stained bioclasts and broken pteropod fragments.

Sample 6401618 #16



The gravel component is comprised of a large coralline bioclast with additional branching corals, stained sub angular bivalve fragments fenestrate bryozoans. The sand fraction has benthic and planktic foraminifera, pteropods fragments coralline fragments, and a biogenic hash.

Sample 6401619 #17



Surpulid encrusted biogenic clasts stained angular mollusc fragments abraided bivalves and fenestrate bryozoans comprise the gravel fraction. The sand percentage includes ostracod tests, benthic foraminifera, broken echinoderm spines and assorted stained angular bioclasts.

Sample 6401620 #18



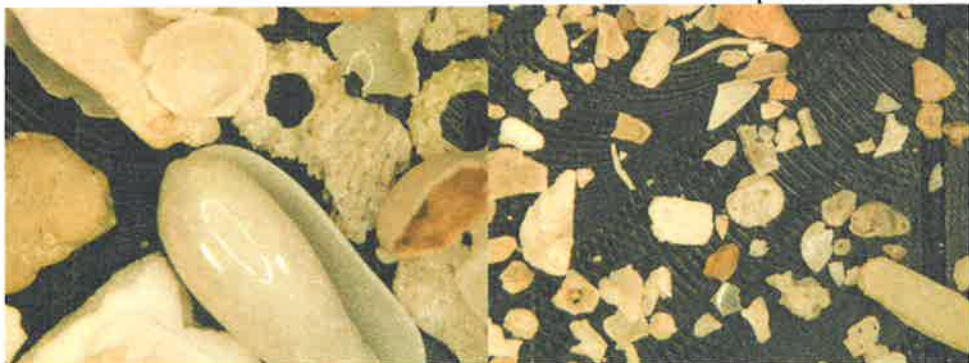
With the exception of the fresh branching bryozoa initiating on an encrusted bioclast and a small piece of fenestrate bryozoan, this gravel is relict stained and sub-angular to rounded in shape. The sand includes bioclasts 65% orange stained sub angular, and a range of bivalves and biogenic hash.

Sample 6401621 #19



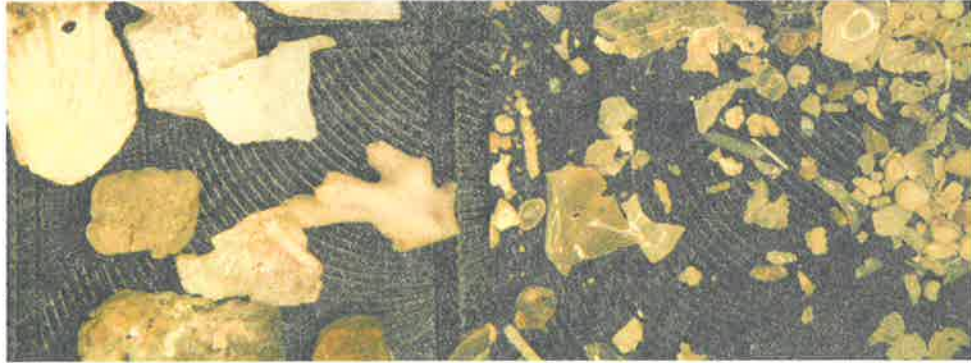
The gravel (LHS) contains relict stained rounded biogenic clasts with encrusted vagrant bryozoans, and angular bioclasts with a fenestrate bryozoan and the sand component is largely reworked biogenic material consisting of stained echinoderm spines, sub rounded bio clasts, fragments of fenestrate bryozoans, bivalves with borings, and benthic foraminifera.

Sample 6401622 #20



A clean well sorted sediment sample with the gravel components containing gastropods, bivalves small echinoderms and a range of relict and intermediate sub rounded bioclasts. The sand too is well sorted 65% angular to sub angular bioclasts, many of the stained, and some fresh angular biogenic fragments.

Sample 6401623#21



Sub rounded relic bioclasts including branching bryozoans encrusted and bored bivalves sub angular and rounded stained bioclasts make up the gravel fraction. The sand percentage includes pteropod fragments, disarticulated ostracods hyaline gastropods and planktic foraminifera.

Sample 6401624 #22



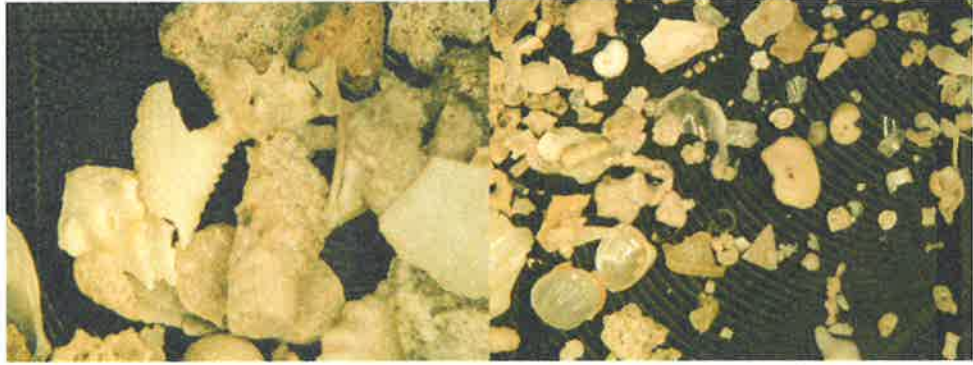
Sub angular bivalve fragments, fresh disarticulated bivalves, intermediate bioclasts, including branching bryozoans and echinoderm shells make up the gravel fraction. The sand percentage includes pteropod fragments, hyaline gastropods. Ostracod tests and a variety of benthic and planktic foraminifera including *Ruber* spp.

Sample 6401625 #23



The gravel fraction (LHS) consists of large sub rounded bioclasts, pteropods, bivalves, and fenestrate bryozoans. The sand percentage includes pteropod fragments, planktic foraminifera, stained and fresh benthic foraminifera, and glauconitic clasts.

Sample 6401627 #25



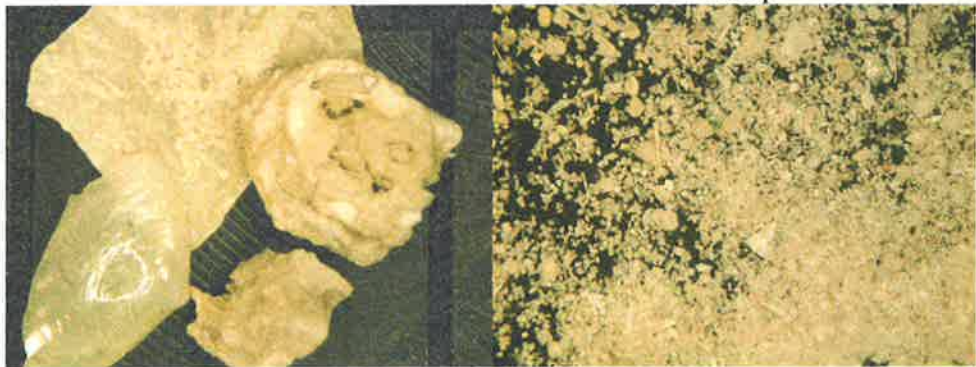
Angular gastropod bivalve and coralline fragments with a range of stained relict bioclasts make the gravel percentage of this sample. The sand (RHS) contains pteropods, planktic foraminifera, disarticulated ostracod tests, angular and rounded bioclasts and some fresh gastropods fragments.

Sample 6401628 #26



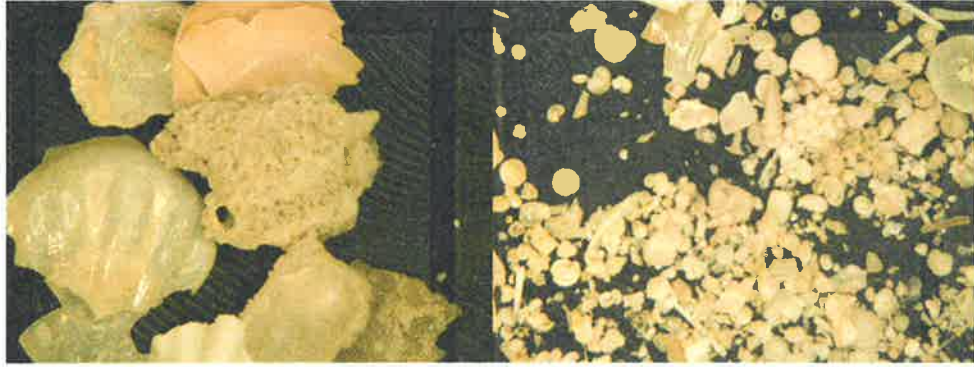
Vagrant and fenestrate bryozoans broken bivalves and abraded bioclasts make up much of the gravel fraction. The sand includes both benthic and planktic foraminifera, mollusc and coralline fragments.

Sample 6401629 #27



The Gravel fraction (LHS) contains disarticulated hyaline bivalves, bryozoan encrusted mollusc fragment and infilled bioclasts. The sand consists of very fine pteropods fragments planktic foraminifera and a fine mollusc hash.

Sample 6401631 #28



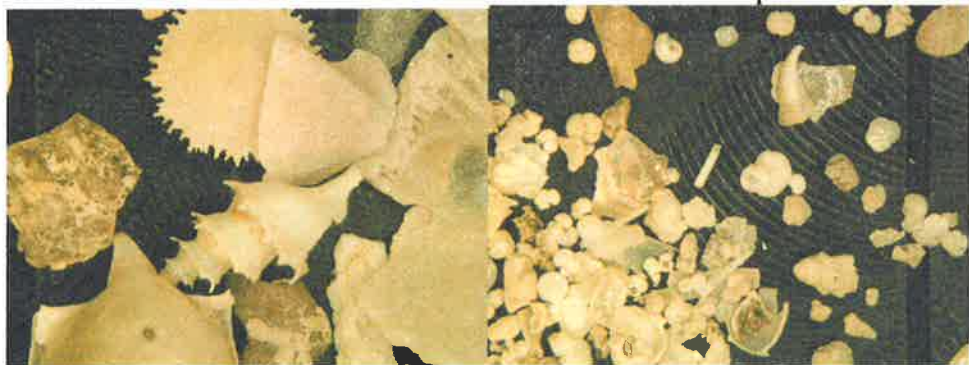
Both broken and intact pteropods, bivalve fragments and abraded bioclasts make up the gravel fraction of this sample (LHS). The sand component contains fine grained biogenic sediments including pteropod fragments, planktic foraminifera and shell hash.

Sample 6401633 #29



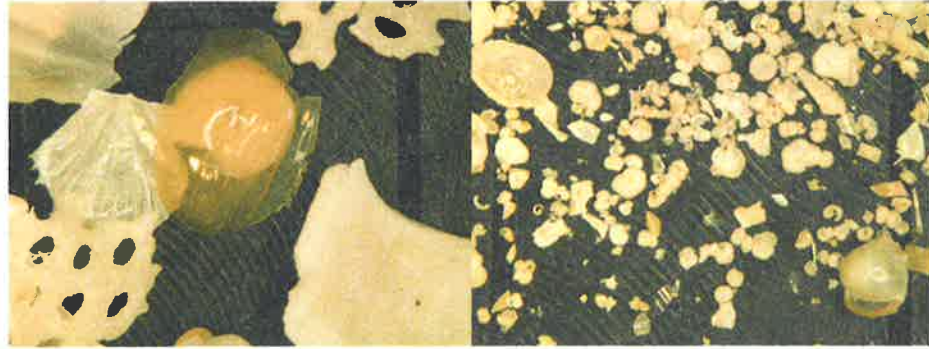
Clean gastropods and pteropods make up the gravel fraction. The sand percentage includes both benthic and planktic foraminifera, pteropods fragments, bivalve and gastropod fragments.

Sample 6401635 #30



The gravel fraction is comprised of ornate gastropods, vagrant bryozoans and solitary corals, pteropods and several surpolid encrusted bioclasts. The sand component contains planktic foraminifera, gastropods, pteropod fragments and stained bioclasts.

Sample 6401637 #31



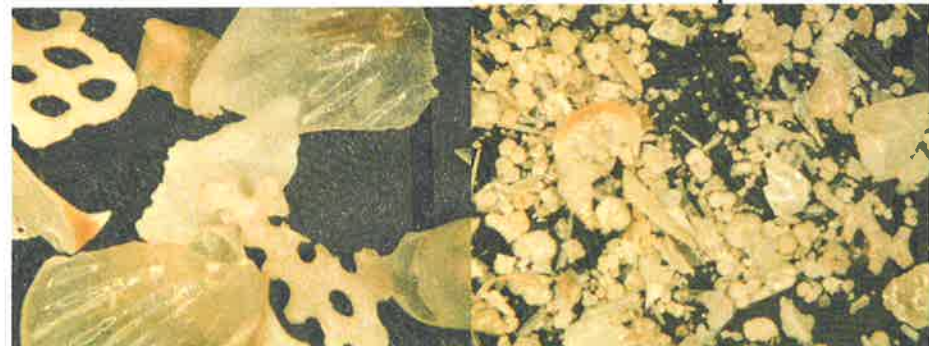
Fenestrate bryozoans, pteropods and ornate bivalves make up the gravel fraction of the sample. The sand percentage contains planktic and benthic foraminifera, pteropods and pteropod fragments, encrusted bivalves and stained angular bioclasts.

Sample 6401639 #32



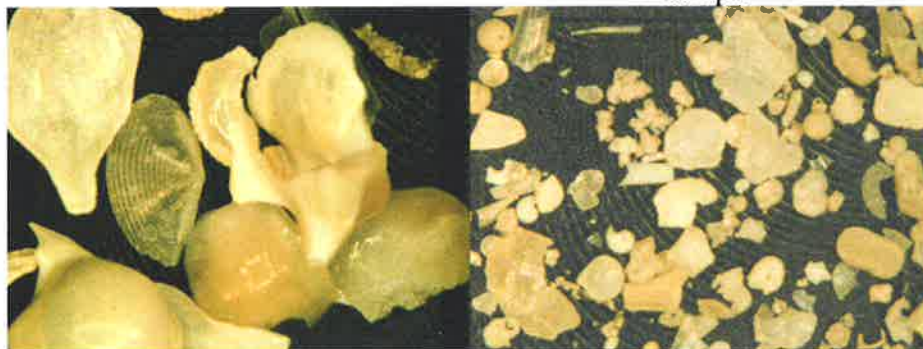
Pteropod and bryozoan make up the majority of the gravel fraction. Where as the sand percentage is largely planktonic foraminifera including numerous *ruber* spp. Pteropods fragments hyaline gastropods and some stained small bioclasts.

Sample 6401641 #33



The gravel fraction (LHS) consists of large pteropods and polished fenestrate bryozoans and the sand percentage is made up of planktic foraminifera pteropod fragments, pieces of fenestrate bryozoans, small gastropods and biogenic hash.

Sample 6401642 #34



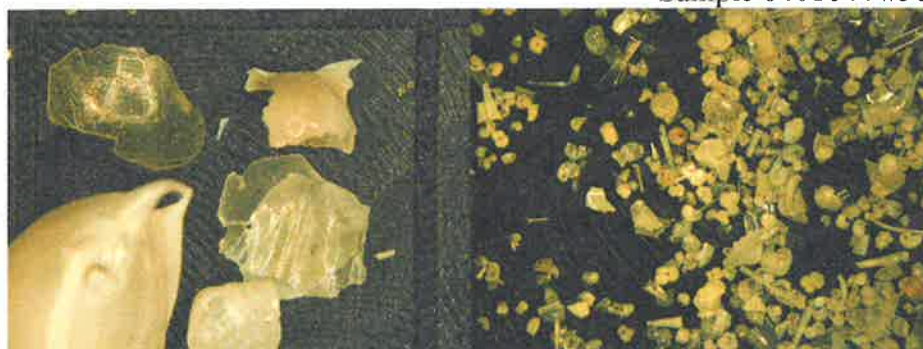
The gravel fraction (LHS) consists of large pteropods (some abraided) and polished branching bryozoans and the sand percentage is made up of planktic foraminifera pteropod fragments, pieces of fenestrate bryozoans, small gastropods and biogenic hash.

Sample 6401643 #35



The gravel component of this sample is largely pteropods with some angular fenestrate bryozoan and ambiguous angular clasts. The Sand fraction contains large numbers of planktic foraminifera (*Ruber* spp.) Pteropod fragments some stained bioclasts and a shell hash.

Sample 6401644 #36



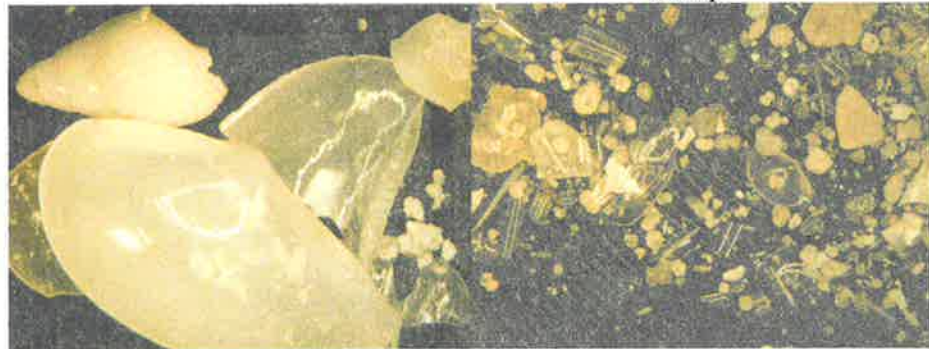
The gravel fraction (LHS) consists of large pteropods (some broken) and bivalves abraided and the sand percentage is made up of planktic foraminifera pteropod fragments, pieces of fenestrate bryozoans, small gastropods and biogenic hash.

Sample 6401645 #37



The gravel fraction (LHS) consists of large encrusted bioclasts (some stained) and pteropods and the sand percentage is made up of planktic and some benthic foraminifera, pteropod fragments, small gastropods and biogenic hash.

Sample 6401646 #38



Large Hyaline bivalves, pteropod fragments make up the gravel fraction (LHS) and the sand percentage has planktic foraminifera, angular and sub-angular molluscs fragments and broken pteropod remains.

Sample 6401648 #39



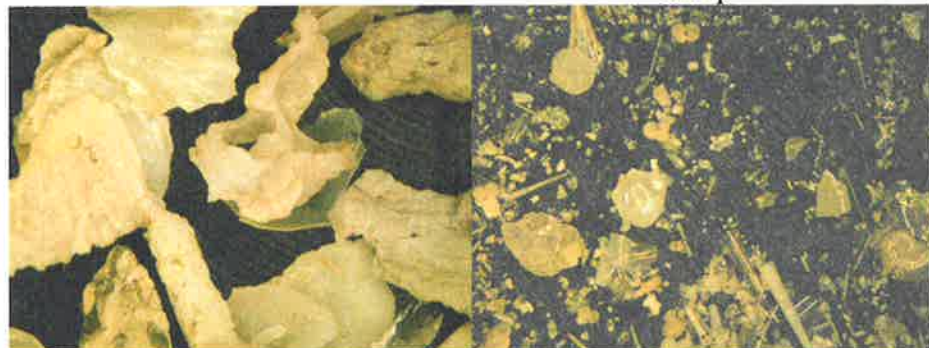
Large worn encrusted bioclasts (some stained) with bivalve fragments make up the gravel fraction (LHS) and the sand fraction contains Pteropod fragments, benthic and planktic foraminifera, molluscs angular grains, and broken fragments of branching bryozoans.

Sample 6401649 #40



The sand percentage is largely stained bioclasts with intermediate and fresh gastropods benthic and planktic foraminifera and small pteropods and pteropod fragments with biogenic hash.

Sample 6401653 #42



Molluscs fragments relict biogenic grains and pteropod fragments make up the gravel fraction (LHS) and the sand sample is largely pteropod fragments and gastropods with some planktic foraminifera.

Sample 6401656 #43



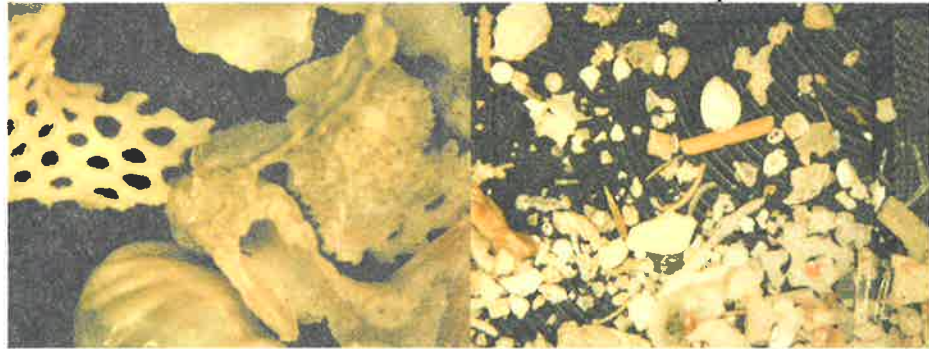
The gravel percentage of this sample contains relict biogenic clasts encrusted disarticulated bivalves and pteropods, the sand sample consists of relict benthic foraminifera, bioclasts with fresh bivalves (some bored) sponge spicules ostracod tests and bioclasts.

Sample 6401660 #44



Stained and infilled pteropods and pteropod fragments, bored echinoderms coralline fragments and branching bryozoa make up the gravel percentage. The sand fraction contains the same material with the addition of disarticulated bivalves and stained bioclasts.

Sample 6401663 #45



The gravel fraction (LHS) consists of fenestrate Bryozoans pteropods and encrusted bored stained bioclasts. The sand fraction of the sample is made up of benthic foraminifera fenestrate bryozoa, pteropod fragments, and a range of biogenic hash.

3.7 Accelerator mass spectrometry dates

The AMS dates of the surficial sediments in this study indicate that the modern depositional rates across the Bonaparte Shelf are low. Sands are dominated by benthic foraminiferal species: some agglutinated, calcitic-porcellaneous, and calcitic-hyaline groups. Benthic porcellaneous foraminifers were most prolific eg. Elphidium spp. Pleistocene calcarenite sediments are also found in the Joseph Bonaparte Gulf, and are inferred to have been deposited in high energy, tide-dominated shelf environments before, and during, the 120 ka highstand (Clarke et al. 2000; 2001)

Core	Water depth	Depth down core	AMS Date
GC003	134	0.0m	2968.000
GC010	117.2	0.0m	5066.000
GC015	64.8	0.0m	3181.000

Table 3.1 The AMS dates of the study area core tops. This information assisted in formulating the average age of the surficial sediments in the high energy tropical shelf environment

3.8 Terrestrial sediment contribution

Two sediment samples from this study (Sediment samples # 6401603 and #6401604), contained a visible quartz fraction. As both were fine grained and ‘frosty’ in appearance, it was thought initially to be aeolian but after application of diluted HCL the ‘frost’ produced gas and uncovered a clean angular transparent quartz grain. This indicated that the quartz grain was being used as a nucleus for the chemical precipitation of calcium carbonate. By default the quartz sands found at this location, at the eastern portal of the Penguin Deeps, are characterised as fluvially derived from a nearby terrestrial source.

Lees (1992) found that quartz sands are generally deposited on the inner shelf in <70 m water depths, mostly in offshore bars which are spatially associated with the river mouths of the Fitzmaurice, Victoria, Keep, Ord and Berkeley rivers

(Figure 3.13). These bars are zoned, with lobes of coarse sands and gravel, and tongues of seaward-fining, silty sands and clayey sands, extending up to 100 km offshore (Lees 1992) While some may represent former shore line facies, anecdotal evidence indicates much of these deposits are Holocene in age and subject to rigorous reworking (pers. comm.. D. Skeen 2004).

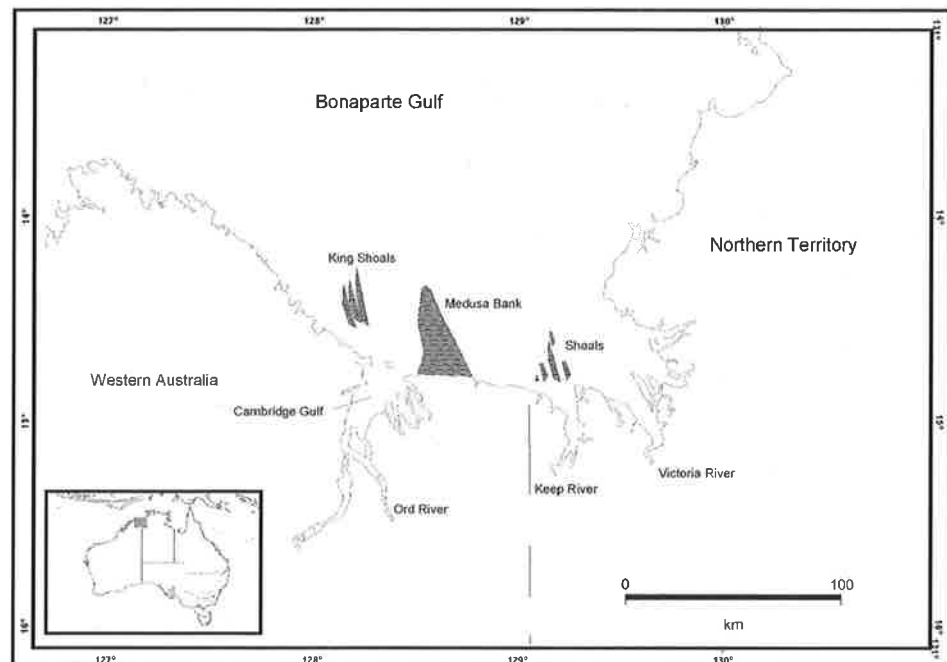


Figure 3.13 The river mouths of the main rivers flowing into the south-west Bonaparte Gulf, and the location of the spatially associated mud deposits, after Clarke et al. (2000).

Sediment near river mouths is dominated by coarse-grained tidal-current orientated sand ridges up to 15m high. Such ridges are being actively deposited off the Ord (King Shoals) and Keep Rivers (un-named shoals- Figure 3.13), predominantly on the left hand side of the river mouths, or ‘down-stream’ of the dominant westward coastal current. Other offshore sediment deposits include the extensive “Medusa Banks”. These are a series of mud banks up to 15m thick that have been generally deposited to the east of the river mouths.

Coarse grained sorted carbonate sands and 'pellets' which occur in channels were identified by Lees (1992) as palimpsest terrestrial material. Wave action and tidal currents prevent the deposition of fine grained material near shore and reworks and redistributes coarse material in shallow water (van Andel and Veevers, 1967, pers. comm., D. Skene 2004). This combined with re-suspension and removal of sediments by currents and cyclone-induced wave energy, can trigger sediment-rich flows off the shelf into deeper water.

Clarke (1997) identified four drowned strandlines on the inner shelf at depths of 20, 25, 28, and 30m between the Ord and Berkeley Rivers. These were interpreted as having formed during stillstands in the Late Pleistocene transgression, and Lees (1992a) suggested that such offshore, coarse-grained sands were blown back on-shore at times of lower SL, to form a series of cheniers along the coastline. These formed proximal to sediment supply, adjacent to several river mouths.

Surficial sediments on the continental shelf exhibit facies variation reflecting the energy gradient (Harris 1994). Unlike other tropical shelves the Bonaparte Shelf region has minimal seagrass cover to baffle, trap and bind shelf sediments. The lack of sea grass cover may be due to:

- Unsuitable substrate.
- Water depth >60m.
- Water temp and salinity variations.
- Erosional activity of macro-tides (>4.8m).
- Frequent storms and cyclones (pers. com. A Heap 2004).
- Regional coastal tidal currents run up to 2.9 knots (Lees, 1992).

Consequently, much of the shelf is described as an erosional surface or a sediment bypass zone (Harris 1994).

Work by van Andel and Veevers (1967) shows that apart from significant deposits directly adjacent to the river mouths, there is no sedimentological evidence to support major terrestrial sediment inputs to modern off shore surficial sediments. While finding terrigenous indicators (feldspars), between the Ord / Victoria River mouths and the Bonaparte Depression, indicates that shelf inputs may continue today, or that the rate of biogenic shelf sediment accumulation rates are low. Recent bathymetric images and the age of the sediment samples from this study support observations of the low accumulation rates on the shelf. The bathymetric images demonstrate that the palaeo-river channels such as the now submerged Victoria River, are generally not in-filled and their rugose nature remains clearly apparent in the bathymetric record (Figure 3.14). This supports the findings of this study, that the fluvial derived terrestrial sediment is being maintained in the near shore environment.

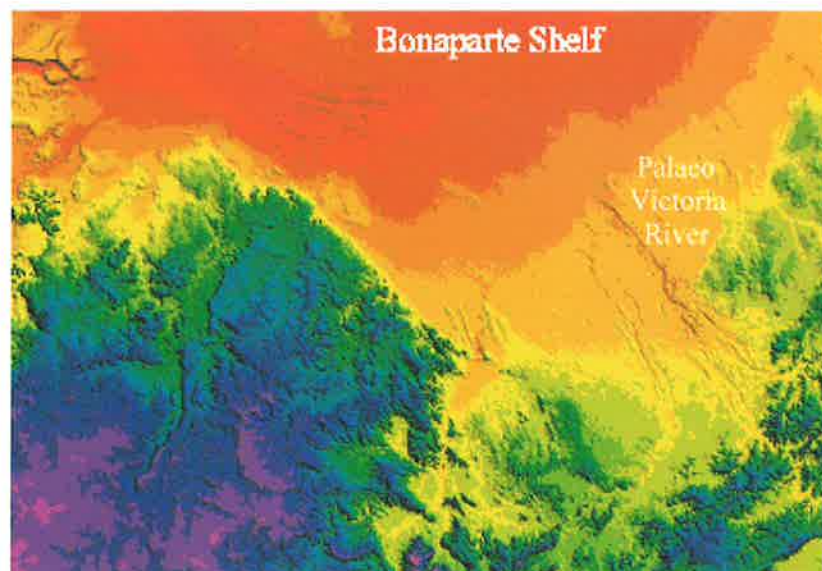


Figure 3.14 The Palaeo Victoria River remains unfilled with sediment as it traverses the southern Joseph Bonaparte Gulf, this indicates that the sediment that enters the Bonaparte Shelf does not make it out towards the depression but stays close to the near shore environments at sea level highstands.

3.9 Results

3.10.1 CaCO_3 across the Kimberley Shelf and Browse Sea Valley

Distribution of the CaCO_3 across the Penguin Deeps (Figure 3.16) from this study and work by van Andel and Veevers (1967) shows no correlation with water depth (Figure 3.15 a) but can be correlated with the grain size. The gravel fraction when it is at <15% of total sample (Figure 3.15 b), tends to have more than 75% CaCO_3 . When the sand fraction (Figure 3.15 b) consists between 50 - 90% it contains 70 – 90% CaCO_3 . When the mud percentage increases the CaCO_3 decreases (Figure 3.15d). Therefore it is apparent that the remaining percentage (named 'other' in figure 3.16) is most likely a very fine grained terrestrial derived sediments, biogenic silica or a combination of these.

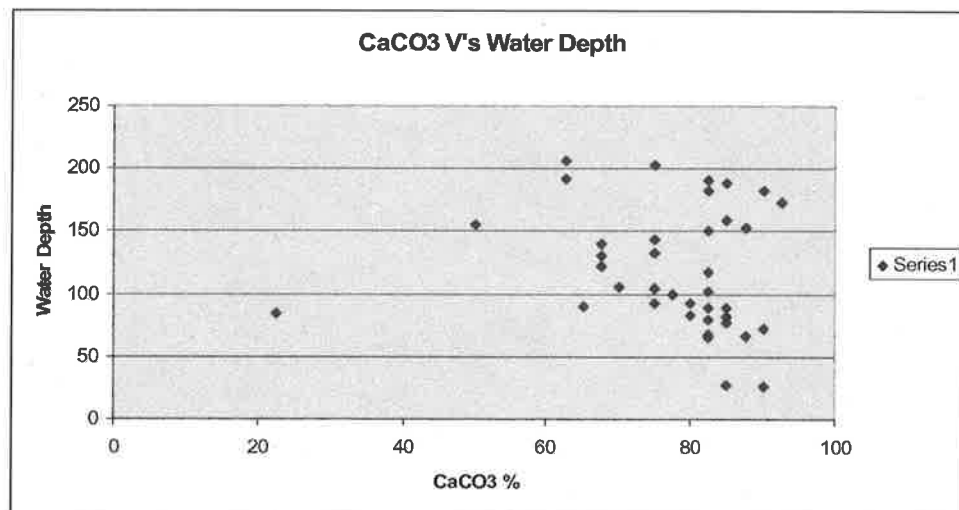


Figure 3.15 a, CaCO_3 percentage and water depth.

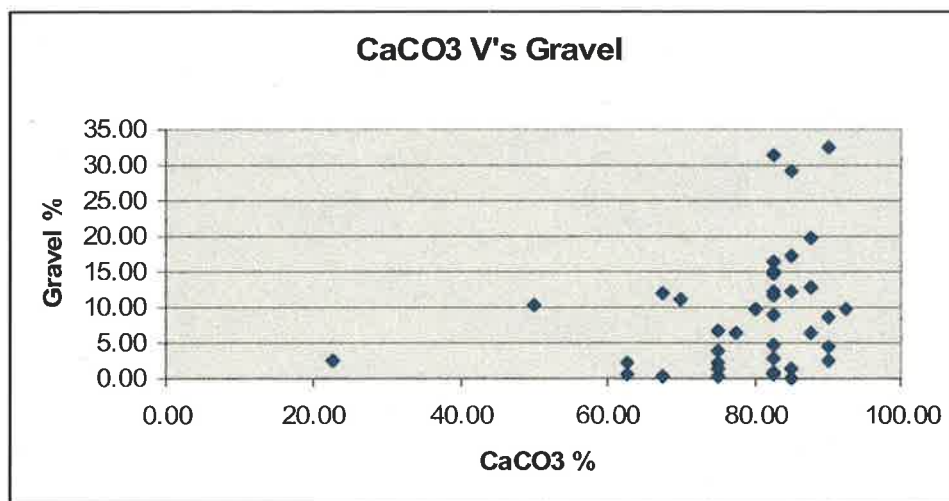


Figure 3.15 b, The relationship between CaCO_3 and gravel fraction.

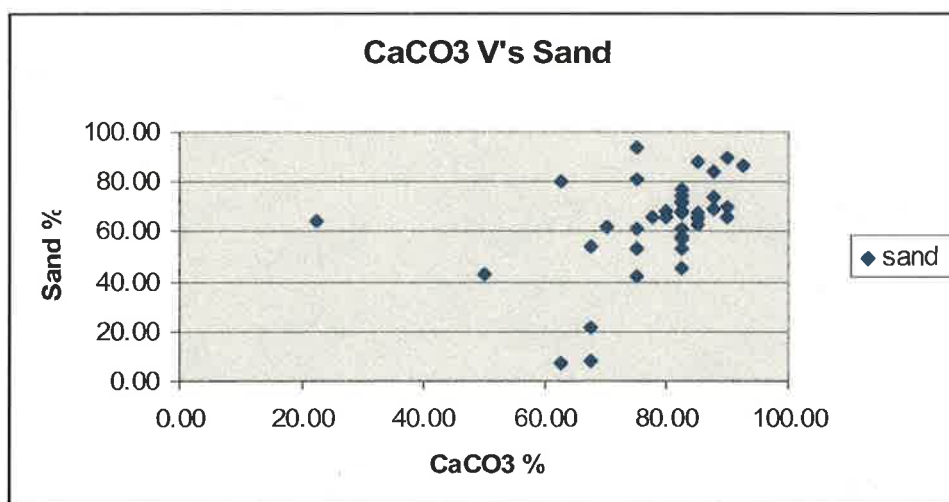


Figure 3.15 c, The relationship between CaCO_3 and sand fraction.

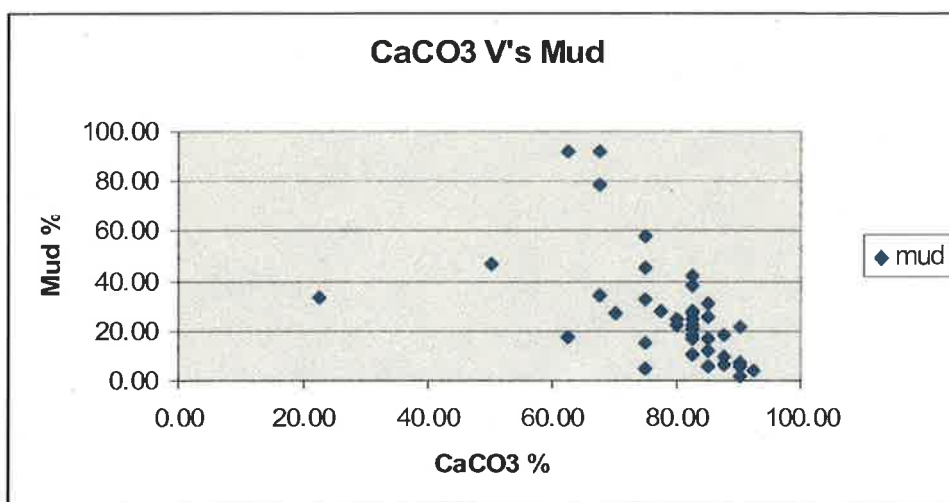


Figure 3.15 d The relationship between CaCO_3 and mud fraction.

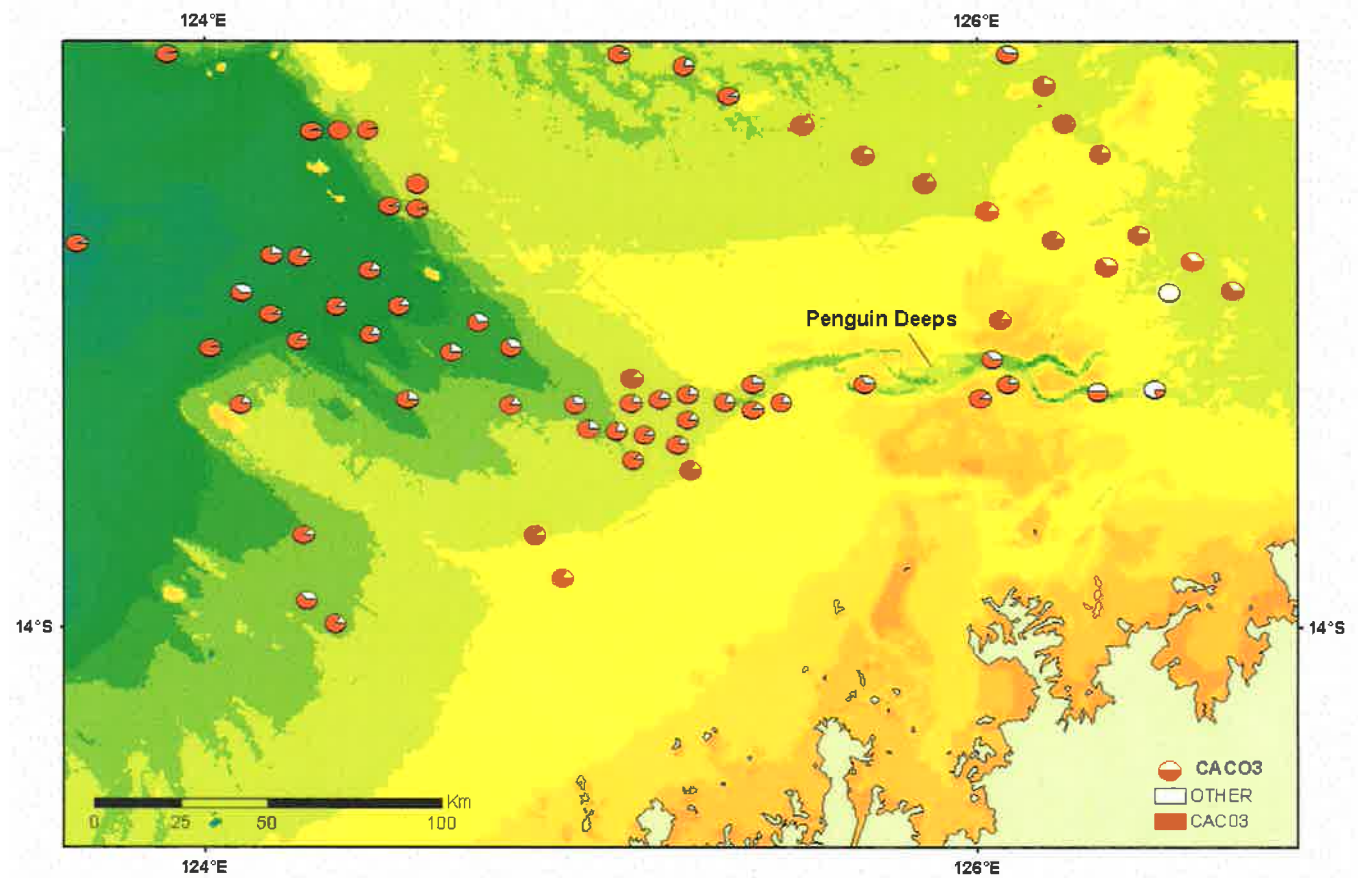


Figure 3.16 Distribution of the CaCO_3 across the Kimberley Shelf and Browse Sea Valley

3.10 Sediment texture

The sediment samples were analysed for grain size (Mud = 0 - 63 μm , Sand = >63 μm - 2000 μm and gravel = > 2000 μm). Gravels are found along the southwest edge of the Bonaparte Shelf and on the two ridges on either side of the Penguin Deeps (Figure 3.2). In most sediment samples, Pteropods make up >30% of the gravel fraction (Appendix 3.1). Many of the sediment samples within the area between 120 – 79m water depth contain the lightweight Pteropod gravels. Sand size sediment is widespread and dominant throughout the study area (Figure 3.17). A significant component (~35%) of the sands in deeper waters, contain planktic foraminifera such as *Globigerinoides ruber*.

Regionally (Figure 3.17), mud is widespread, and found mostly at the entrance to the Penguin Deeps. Mud is the main component of sediments within the basin depression northeast of Penguin Deeps and also the Browse Sea Valley. Whereas, sediment samples near the basin margin contain are sand dominated.

Sand fraction elements were classified using the Geoscience Australian Sedimentology Laboratory nomenclature (Radke 2000) as recent, intermediate and relict (Figure 3.18) as described in the methods section of this study. Distributions of the recent sand fraction are found both within the Penguin Deeps itself and across the Penguin Deeps Fan. Little recent sediments were found landward of the barrier bar at the mouth of the Penguin Deeps as it enters deeper water. The intermediate component of the sand fraction is widespread, often > 50% of the sample, whereas the

relict percentage, although wide spread, is more pronounced in areas of high topographical variation.

The distribution of the recent, intermediate and relict percentages of the gravel fraction (Figure 3.19) reveals that there is little recent gravel.

Samples containing >15% recent gravel, are located at the Kimberley Shelf, shelf break and at the entrance to the Penguin Deeps. The gravel intermediate percentage, is more often located on the northern side of the Browse Sea Valley, along the Penguin Deeps and other areas of high topographical variation. The relict component of the gravel fraction, is most abundant. This is generally > 50% of the gravel fraction and is found across the study region with the exception of the Kimberley Shelf and the entrance to the Penguin Deeps (Figure 3.17).

3.11 Total Organic Carbon

This study shows that the Total Organic Carbon (TOC) distributions across the region range from 0.1 to 0.65%. TOC values increase with the increasing percentage of mud within the sediments (Figure 3.21). This relationship has been well established (Thompson and Eglinton 1978; Mayer 1994; Hedges et al. 1995; Bergamaschi, et al. 1997) and is due largely to the amount of surface area of an individual sediment grain (smaller grain size = larger comparative surface area). The TOC links with physical associations, grain coatings and enzyme penetrations, however, are still poorly understood. The lowest TOC values are spatially associated with the barrier bar area and on either side of the Penguin Deeps and the highest values are generally found in deeper water to the west of the Penguin Deeps Fan (Figure 3.20).

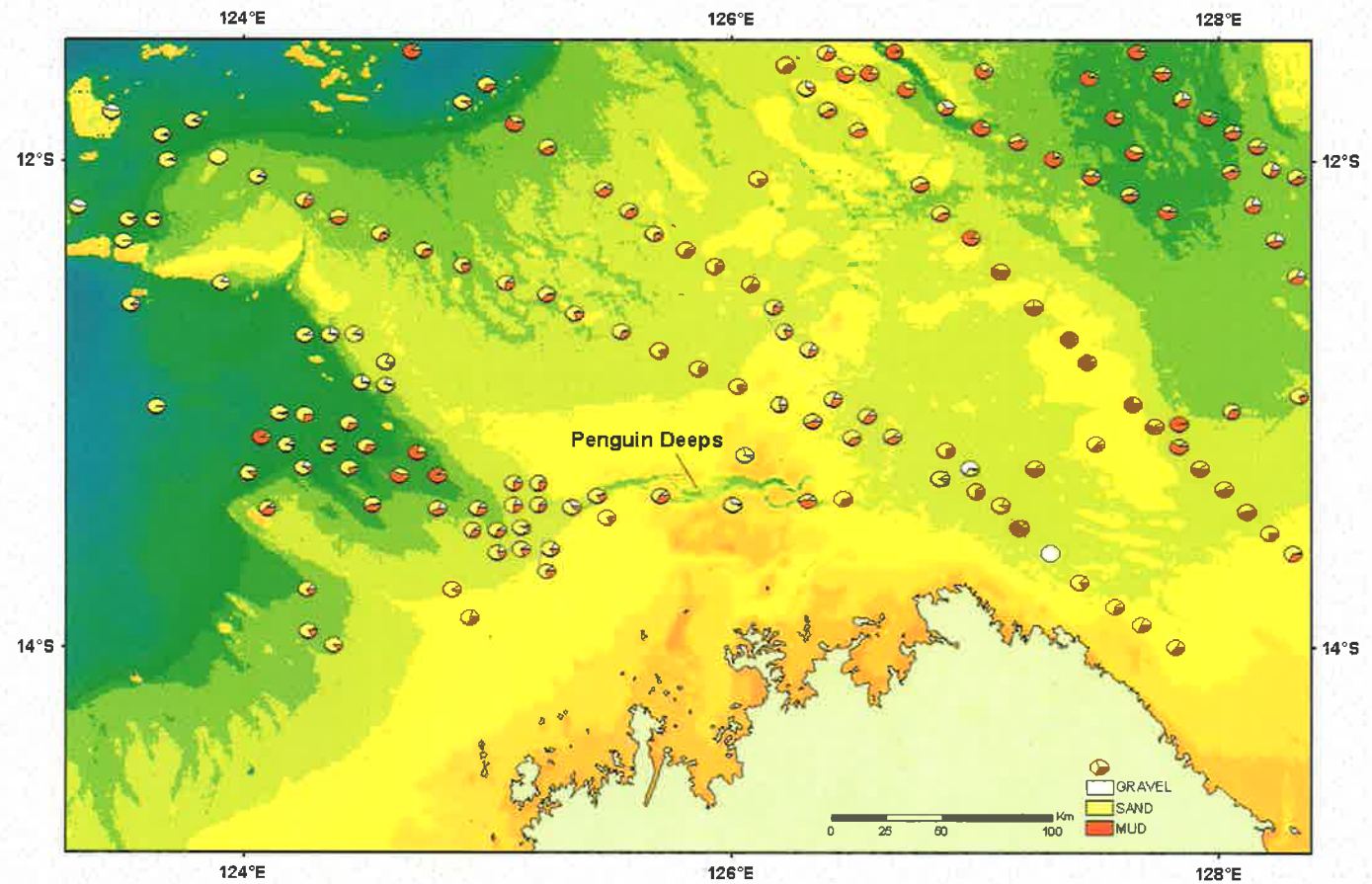


Figure 3.17 Grain size analysis of the surficial sediments of this studies samples, combined with data from van Andel and Veevers (1967).

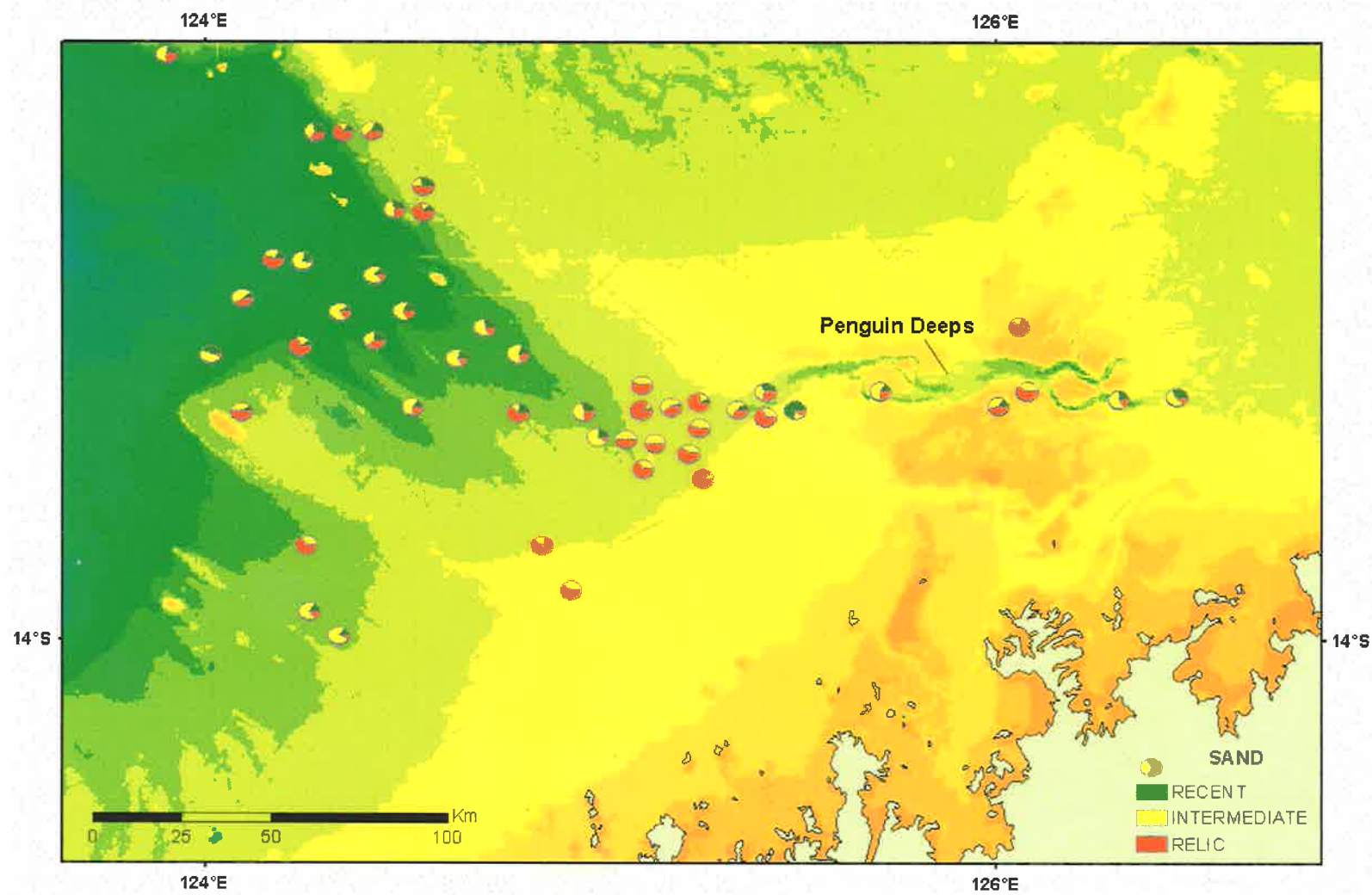


Figure 3.18 Relative age composition of the Kimberley Shelf surficial sand fraction, from this study.

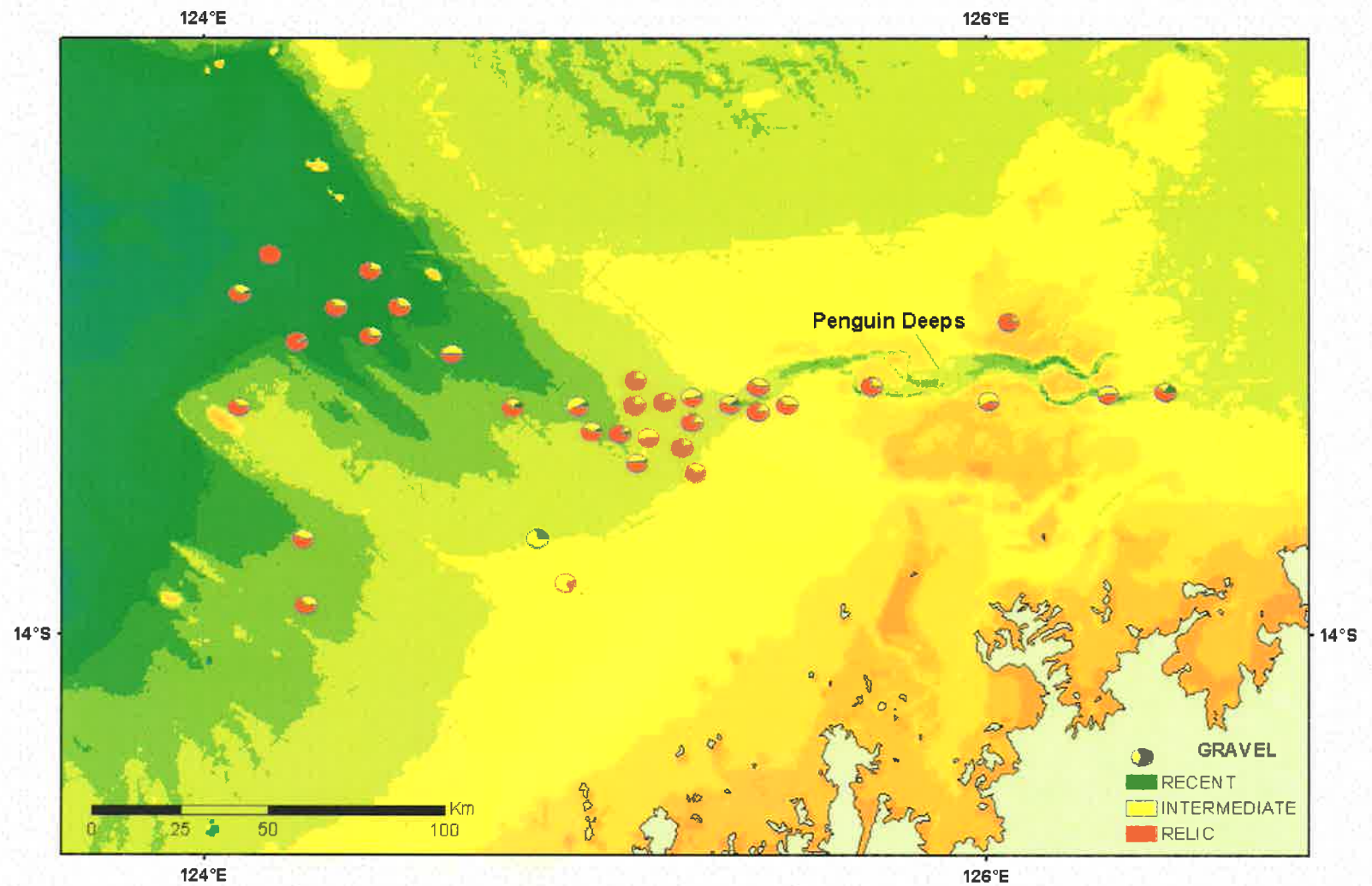


Figure 3.19 Relative age composition of the Kimberley Shelf surficial gravel fraction (samples from this study). This figure indicates that the majority of the gravel fraction is relict in nature.

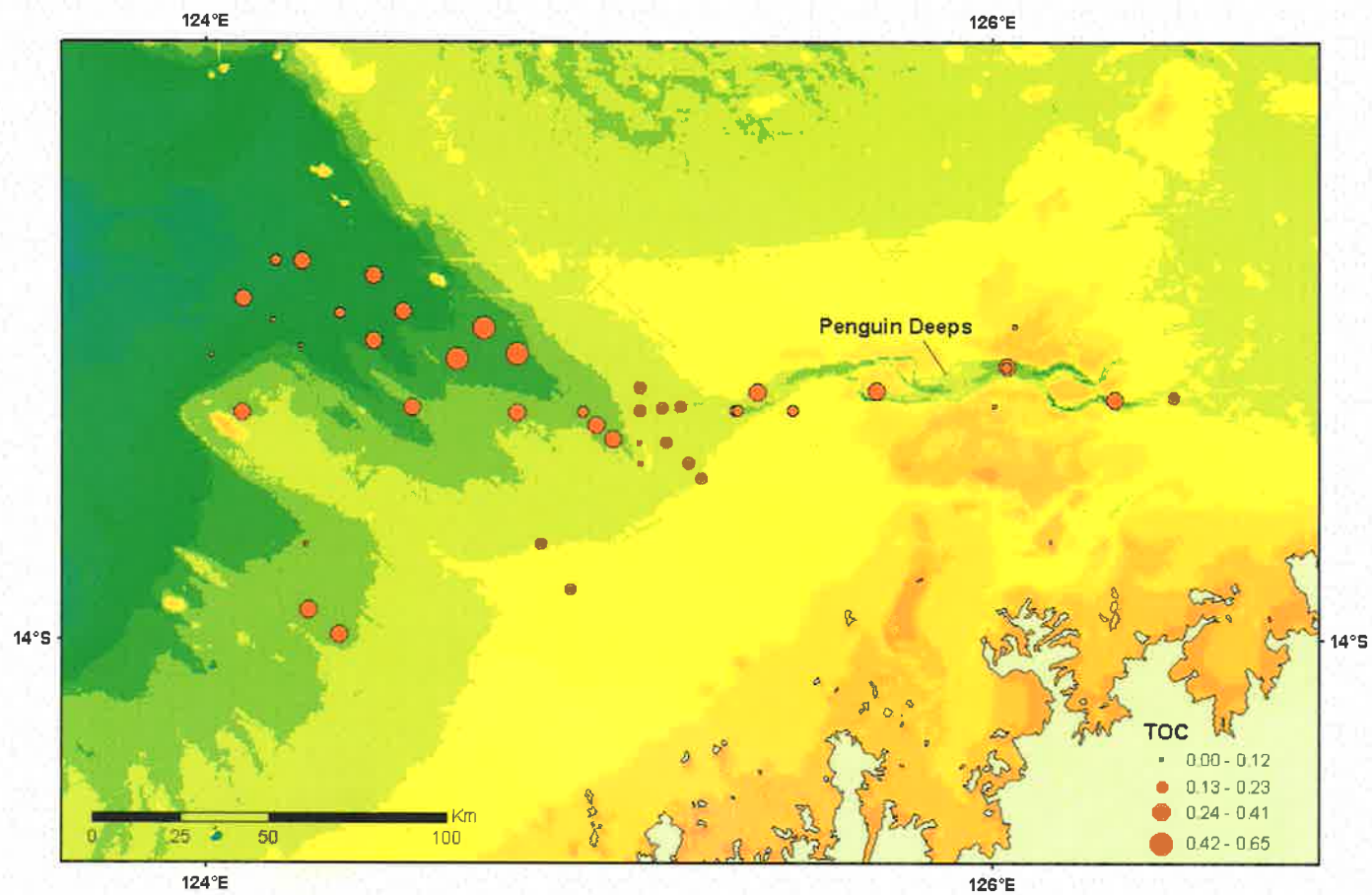


Figure 3.20 Total Organic Carbon (TOC) percentages of the Kimberley Shelf surficial sediments, from this study.

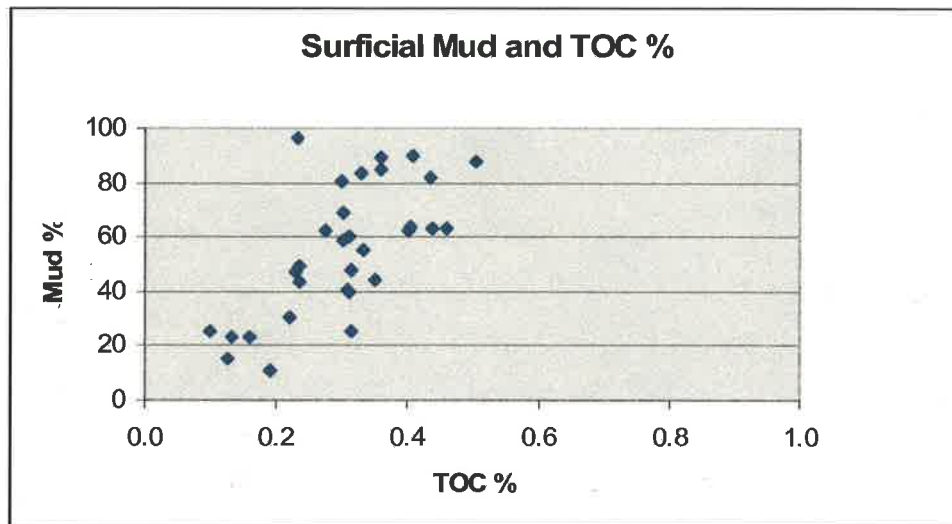


Figure 3.21 The relationship of the percentage of mud size particles and the Total Organic Carbon values.

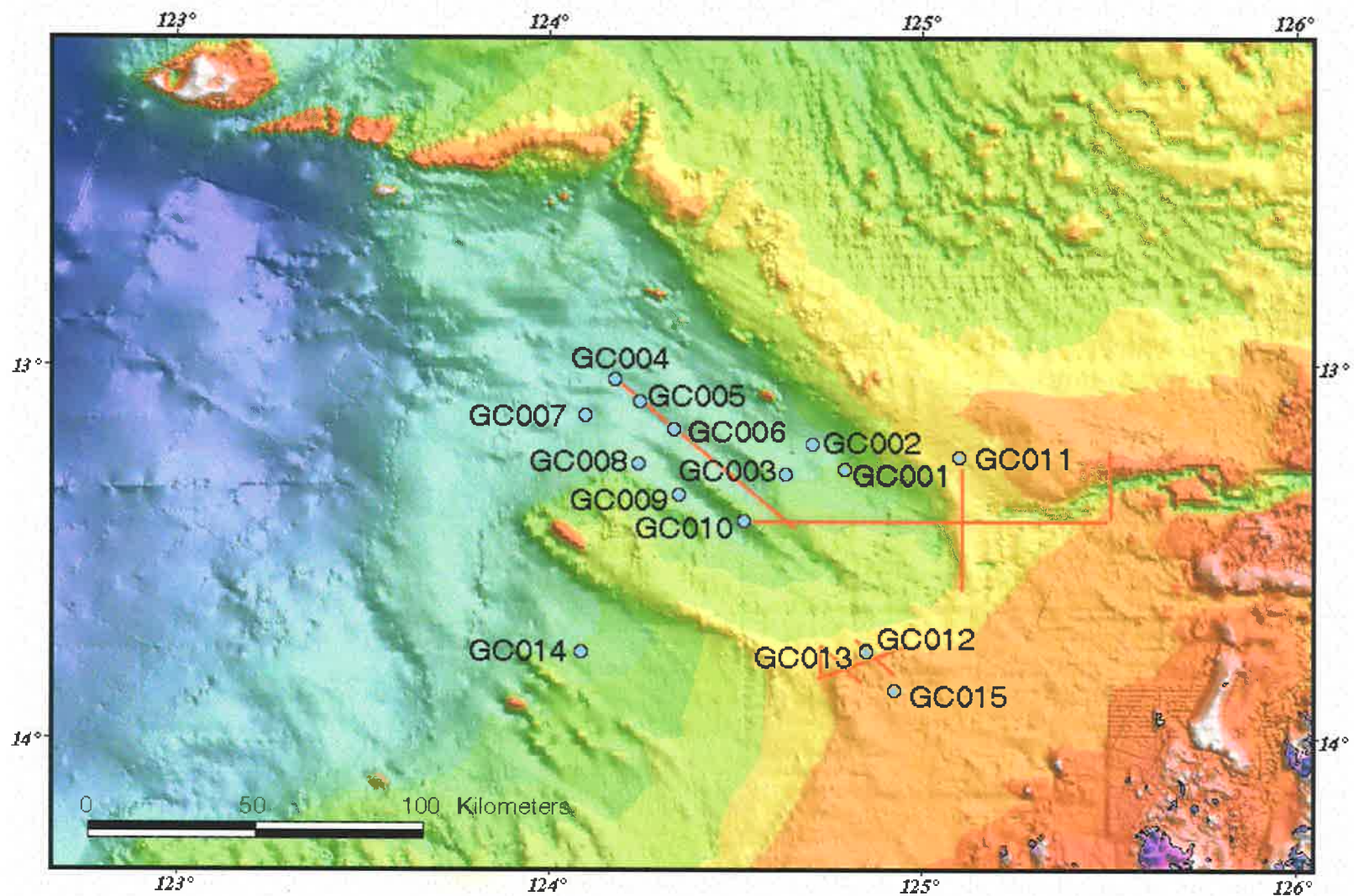


Figure 4.1 Core sites cross the Kimberley Shelf and Browse Sea Valley

Chapter 4 Sediment Core Observations and Supporting Data.

4.1 Introduction

A series of fifteen core sites were selected for the acquisition program. Nine of the fifteen attempted during survey 225 (Figure 4.1) yielded suitable sediment for analysis, and are described in detail. Water depths ranged from 64m – 205m with the majority of cores taken from the Browse Sea Valley (Figure 1.1), west of the Penguin Deeps channel. Four other cores were attempted as adjacent control sites (cores 12 – 15).

Sediment analysis of the cores reveals a range of inferred facies defined by textural and geo-chemical properties that identify accumulation rates and potential provenances across a variety of environmental settings. All sediments samples were given an initial appraisal to determine the percentage of fresh intermediate and relict fraction of the sand and gravel grain sizes (Appendix 3.1, Figures 3.18, 3.19).

4.2 Accelerator Mass Spectrometry Dating

4.2.1 Method

Ten benthic foraminiferal samples from the cores were carbon 14 dated, via the Accelerator Mass Spectrometry (AMS) method using the foraminifera *Elphidium crispum* and *Elphidium charlottense* (Figure 4.2). All of the foraminifera used in this process were free from any evidence of transport, degradation or contamination, they were whole, undamaged and non-stained. This species of foraminifera was selected due to its robust preservation and widespread

distribution across the shelf. They are both infaunal, benthic, marine, free living, foraminifera found in temperate to warm waters. They generally live within 30-35 ‰ salinity and in 0 – 25m water depth (Murray 1991).

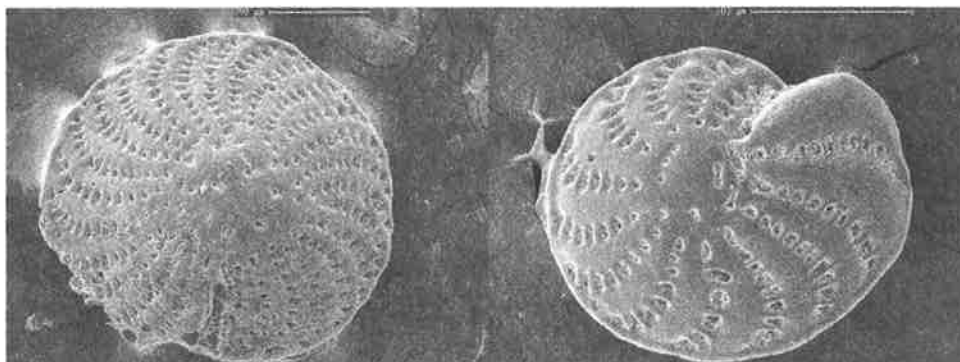


Figure 4.2 The foraminifera used for AMS dating (Glenn and Collins 2004) were predominately; *Elphidium crispum* (on the left) and *Elphidium charlottense* (on the right).

4.2.2 Accelerator mass spectrometry results

The AMS dates assisted in calculating the overall accretion rates of near surface sediments. These dates range from 2968 – 11880. The accretion rates of 16.82 cm/ka to 223.21 cm/ka, are calculated by dividing depth of sediment, by the number of years elapsed, and using the assumption that sediment accumulation was continuous. Yet being in a region with sediment pulses of reworked shelf material from the cyclone activity and monsoonal storms injecting terrestrial sediments seasonally, this assumption is most probably, unlikely.

Lab #	Core	Water depth	Depth down core	AMS Date	AMS error	accumulation rate cm per ka
6401678	GC001	130	1.75m	7805.000	45.000	
6401679	GC003	134	0.0m	2968.000	40.000	
6401680	GC003	134	0.8m	7723.000	45.000	16.82
6401681	GC003	134	1.8m	8225.000	60.000	199.2
6401692	GC010	117.2	0.0m	5066.000	40.000	
6401693	GC010	117.2	0.9m	9155.000	50.000	22.01
6401694	GC010	117.2	1.9m	11432.000	55.000	43.91
6401695	GC010	117.2	2.9m	11880.000	55.000	223.21
6401664	GC015	64.8	0.0m	3181.000	40.000	
6401665	GC015	64.8	0.85m	8140.000	45.000	017.14

Table 4.1 Gravity cores yielded AMS dates and accumulation rates, which ranged from 16.82 cm/ka to 223.21 cm/ka,

4.3 Total Organic Carbon values of the sediment cores

4.3.1 Method.

The Geoscience Australia standard operating procedure was used

SOP # TOC-2003-1.0 (Watson, Ramsay and McLachlan 2003).

4.3.2 Total Organic Carbon Results

The total organic carbon (TOC) values of the cores illustrate a change in percentage values with no strong divergence of both the surficial and down core sediment values (Table 4.2).

TOC% values range from: 0.161 – 0.505%, with one anomalous value at 1.501% (5.3 times the average value) which may result from a fragment of a life form or coprolite. Textural–geochemical relationships varied down core, 2 cores showing an increase of TOC% towards the top, 4 cores had values that varied throughout the core, and one core showing a decrease of TOC% towards the top.

Sample number	Sample type	Latitude	Longitude	TOC %	CaCO ₃ %	Down Core Depth
6401676	GC001	-13.274767	124.789833	0.51	68.00	0.0m
6401677	GC001	-13.274767	124.789833	1.50	75.00	1.0m
6401678	GC001	-13.274767	124.789833	0.44	82.00	1.75m
6401666	GC002	-13.208200	124.705400	0.46	74.00	0.0m
6401667	GC002	-13.208200	124.705400	0.31	87.00	0.85m
6401668	GC002	-13.208200	124.705400	0.28	94.00	1.5m
6401669	GC002	-13.208200	124.705400	0.24	92.00	1.8m
6401679	GC003	-13.286533	124.635433	0.44	75.00	0.0m
6401680	GC003	-13.286533	124.635433	0.31	81.00	0.8m
6401681	GC003	-13.286533	124.635433	0.24	90.00	1.8m
6401682	GC004	-13.034873	124.173557	0.19	82.00	0.0m
6401683	GC004	-13.034873	124.173557	0.13	84.00	0.58m
6401684	GC005	-13.089233	124.240183	0.32	83.00	0.0m
6401685	GC005	-13.089233	124.240183	0.40	90.00	0.7m
6401686	GC005	-13.089233	124.240183	0.30	89.00	1.55m
6401687	GC005	-13.089233	124.240183	0.30	86.00	1.7m
6401688	GC005	-13.089233	124.240183	0.35	89.00	2.52m
6401689	GC005	-13.089233	124.240183	0.33	83.00	3.05m
6401690	GC005	-13.089233	124.240183	0.31	84.00	3.6m
6401691	GC005	-14.089233	125.240183	0.23	88.00	4.57m
6401672	GC007	-13.126467	124.093133	0.30	90.00	0.1m
6401673	GC007	-13.126467	124.093133	0.36	90.00	0.4m
6401674	GC007	-13.126467	124.093133	0.40	84.00	1.05m
6401675	GC007	-13.126467	124.093133	0.22	84.00	2.1m
6401670	GC008	-13.256390	124.238323	0.13	94.00	0.0m
6401671	GC008	-14.256390	125.238323	0.23	93.00	0.85m
6401692	GC010	-13.409680	124.521067	0.31	81.00	0.0m
6401693	GC010	-14.409680	125.521067	0.33	84.00	0.9m
6401694	GC010	-15.409680	126.521067	0.36	84.00	1.9m
6401695	GC010	-16.409680	127.521067	0.41	83.00	2.9m
6401664	GC015	-13.869317	124.924487	0.16	83.00	0.0m
6401665	GC015	-13.869317	124.924487	0.10	87.00	0.85m
6401702	GC015	-13.869317	124.924487		88.00	0.3m

Table 4.2 TOC and CaCO₃ values down core

A linear relationship is apparent between TOC values and mud%. (Figure 4.3 a) It illustrates an increase in the TOC% in relation to mud % of the core sediments as in the surficial sediments. The relationship is evident when TOC% is plotted against CaCO₃ (Figure 4.3 b) TOC% increasing with a decrease of CaCO₃, and a linear uniform relationship with TOC% values when plotted against core depth (Figure 4.3 c).

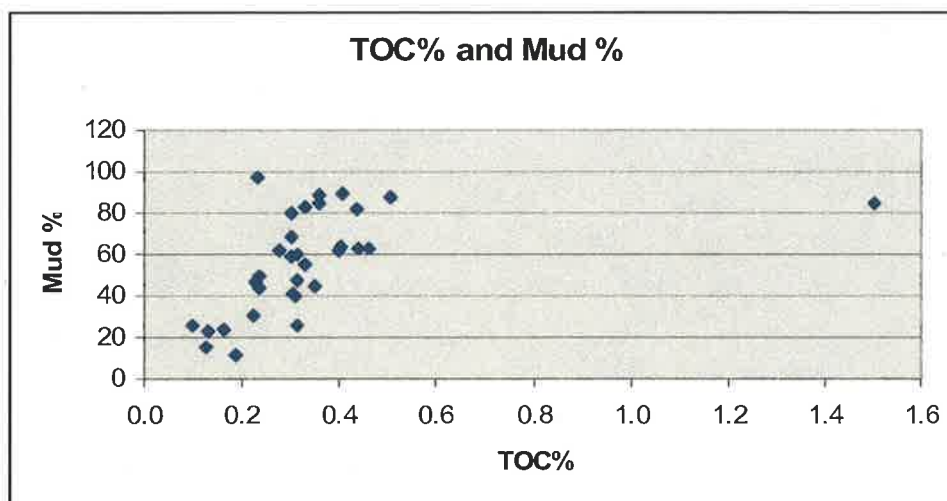


Figure 4.3 a, TOC percentage and Mud Percentage

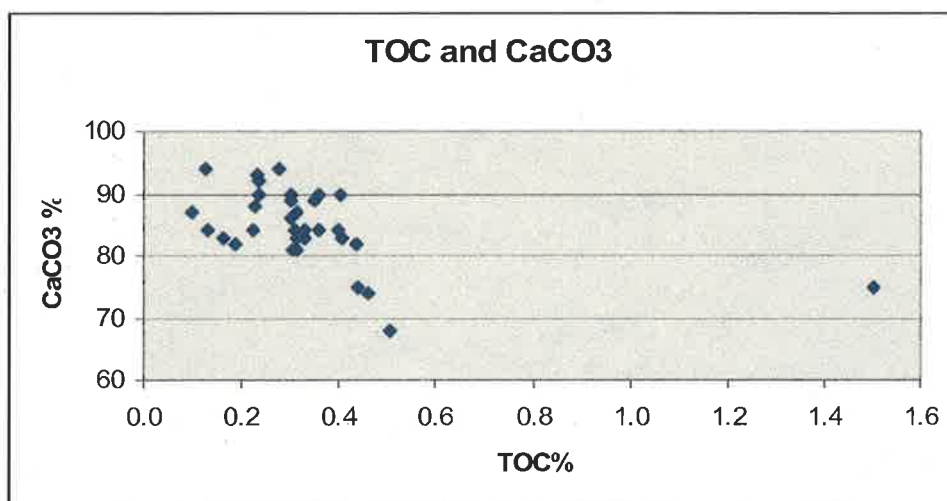


Figure 4.3 b, TOC Percentage and CaCO₃ Percentage

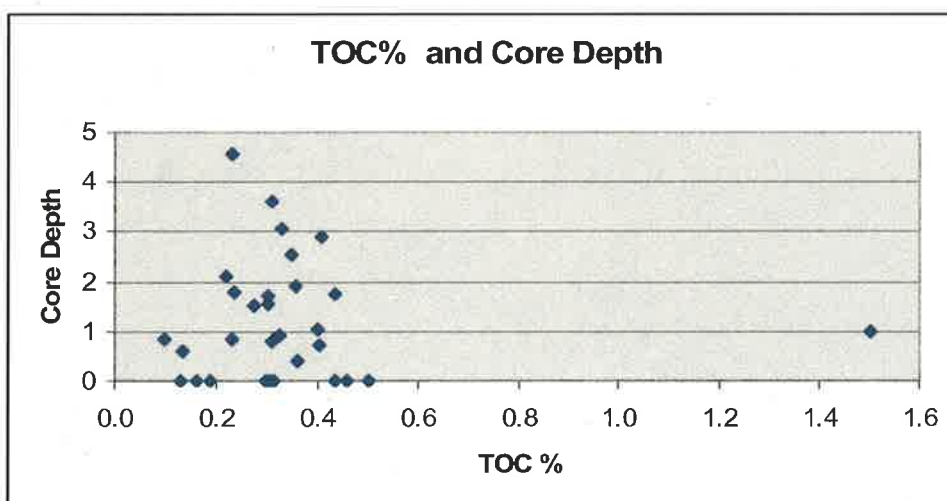


Figure 4.3 c, TOC Percentage and Core Depth.

4.4 Core Sediment Colour

4.4.1 Method

The method used is the method adhered to by Geoscience Australia Sedimentary laboratory. Whereby the colour of the sediment sample was determined by direct comparison with colour charts (Munsell, 2000). When the colour was strongly variegated, the extreme hues were recorded. Where there was lesser colour variation, the average hue was determined on the blurred image when the sample was moved to and fro.

4.4.2 Observations

Colour analysis of the cores showed that the majority of the core sediment 'wet' ranged within the 5y 5 2 - 5y 6 3 band, in common terms this is a drab olive to khaki colour.

4.5 Core Sediment Character

4.5.1 Methods

The grain size analysis was undertaken using the Geoscience Australia SOP for the Malvern Laser Particle Size (grainsize) Analyser.

SOP Number: PMD-SED-SOP-2 (Watson, Ramsay and McLachlan 2002)

4.5.2 Wet sieve

The sample was washed through two nested sieves Gravel ($> 2000 \mu\text{m}$) Sand ($63 - 2000 \mu\text{m}$) and remainder was the Mud fraction ($< 63 \mu\text{m}$) which was decanted, spun and dried. All samples were dried in a low heat oven ($\sim 35^{\circ}\text{C}$.) for 24 hours. The dried samples were weighed and percentages of the fractions were ascertained.

The wet sieve and laser grain size analysis indicated that while much of the sediment was a muddy sand to a sandy mud, biogenic gravel was present in almost all samples (Table 4.3). This was usually in the form of large pteropods, gastropods, bivalves, benthic foraminifera and coral fragments. The microscope analysis of two grain sizes, sand and gravel, were undertaken separately to determine the percentages of relict intermediate and fresh material (Table 4.3).

This analysis showed variation down core in response to the prevailing energy during deposition phases but more so in many cases the bioturbation from annelids, gastropods and bivalves.

4.6 Sediment Summary

4.6.1 Summary

The gravity cores from the Penguin Deeps Fan, mainly consist of a muddy biogenic calcareous sand, though all show diversity in texture, age and sediment type. The TOC values of the sediments show no strong pattern of variation down core.

4.6.2 Interpretation

Nine cores were bulk-sample analysed and all but two cores showed a reduction in carbonate percentage towards to top of the core. No biogenic silica was noted with microscope analysis of the sand fraction.

The relative decrease in CaCO_3 towards the top of the core can be explained in two ways, either and decrease in the amount of CaCO_3 sediments entering the depositional record or an increase in terrestrial sediment. The more

comprehensively dated cores showed a decrease in the deposition rate towards the core top. This decrease and the unlikelihood of increased input from terrestrial sources in the late Holocene; best explains the geochemistry amongst the cores. The available sediment has already been transported off the shelf and into the deposition zones, the slow down in accumulation rates corresponding to available material. The textural variation of the cores may result from the effects of SL over time but more likely the difference is due to the reworking, both biogenic and physical, from the infaunal biota and cyclones/storms respectively.

The regional climate regime has been relatively stable over the mid to late Holocene (Wyrwoll et al. 2001). Regionally, too, vegetation has established a dynamic equilibrium (Hantoro 1997) and wind directions stabilised with the onset of the monsoon 14ka years before present (Wyrwoll et al. 2001). So a climate driven change is an unlikely explanation for the change in the nature of sediments from the Kimberley Shelf. Climate stability also argues against the possibility of variation in fluvial inputs throughout the Holocene.

The argument for a decrease in carbonate material being introduced to the accumulation centres, shows promise, as the shelf today is basically a 'shaved shelf' (James et al. 1994) with little carbonate production / deposition. While there are high production rates on the shelf edge, much of this production is Halimeda spp., which is easily comminuted to very fine particles (aragonite needles / Mg-calcite crystals) which are deposited in lower energy environments, off shelf or deposited as muds (which are easily resuspended and transported). The more robust and heavier material is deposited closer to the production site and does not appear to have a wide distribution across the Bonaparte Shelf.

Core Sediments

Sample No	Core No	lat	Lon	Down Core	Gravel	Sand	Mud	Recent sand	Inter sand	Relic sand	Recent gravel	Inter gravel	Relic gravel
6401676	GC001	13.27477	124.78983	0.0m	0.80	11.56	87.65	0.00	0.00	0.00	0.00	0.00	0.00
6401677	GC001	13.27477	124.78983	1.0m	0.56	14.51	84.93	45.00	50.00	5.00	0.00	0.00	0.00
6401678	GC001	13.27477	124.78983	1.75m	0.36	17.92	81.73	30.00	60.00	10.00	0.00	0.00	0.00
6401666	GC002	13.20820	124.70540	0.0m	2.98	33.91	63.11	0.00	0.00	0.00	0.00	0.00	0.00
6401667	GC002	13.20820	124.70540	0.85m	5.97	46.53	47.50	30.00	50.00	20.00	0.00	0.00	0.00
6401668	GC002	13.20820	124.70540	1.5m	7.70	30.06	62.24	25.00	6.00	15.00	0.00	0.00	0.00
6401669	GC002	13.20820	124.70540	1.8m	13.98	36.79	49.24	20.00	60.00	20.00	0.00	95.00	5.00
6401679	GC003	13.28653	124.63543	0.0m	0.30	36.55	63.15	0.00	0.00	0.00	0.00	0.00	0.00
6401680	GC003	13.28653	124.63543	0.8m	0.07	39.60	60.33	30.00	65.00	5.00	0.00	0.00	0.00
6401681	GC003	13.28653	124.63543	1.8m	0.13	56.41	43.46	30.00	65.00	5.00	0.00	0.00	0.00
6401682	GC004	13.03487	124.17356	0.0m	1.26	87.66	11.09	0.00	0.00	0.00	0.00	0.00	0.00
6401683	GC004	13.03487	124.17356	0.58m	3.47	73.21	23.32	0.00	0.00	0.00	0.00	0.00	0.00
6401684	GC005	13.08923	124.24018	0.0m	1.21	73.48	25.31	30.00	50.00	20.00	0.00	75.00	25.00
6401685	GC005	13.08923	124.24018	0.7m	1.43	34.56	64.01	30.00	50.00	20.00	0.00	50.00	50.00
6401686	GC005	13.08923	124.24018	1.55m	1.04	40.03	58.93	25.00	30.00	45.00	0.00	0.00	100.00
6401687	GC005	13.08923	124.24018	1.7m	1.16	29.80	69.04	10.00	55.00	35.00	0.00	20.00	80.00
6401688	GC005	13.08923	124.24018	2.52m	4.21	51.38	44.40	15.00	45.00	35.00	15.00	15.00	70.00
6401689	GC005	13.08923	124.24018	3.05m	1.75	42.93	55.31	20.00	60.00	20.00	10.00	40.00	50.00
6401690	GC005	13.08923	124.24018	3.6m	2.39	58.01	39.60	15.00	45.00	40.00	0.00	40.00	60.00
6401691	GC005	14.08923	125.24018	4.57m	4.00	49.02	46.98	25.00	55.00	20.00	0.00	0.00	0.00
6401672	GC007	13.12647	124.09313	0.1m	2.54	17.22	80.24	0.00	0.00	0.00	0.00	0.00	0.00
6401673	GC007	13.12647	124.09313	0.4m	0.22	14.89	84.89	40.00	45.00	15.00	0.00	0.00	0.00
6401674	GC007	13.12647	124.09313	1.05m	2.23	35.58	62.19	20.00	35.00	45.00	0.00	20.00	80.00
6401675	GC007	13.12647	124.09313	2.1m	7.22	62.50	30.28	20.00	30.00	50.00	0.00	0.00	0.00
6401670	GC008	13.25639	124.23832	0.0m	21.81	62.66	15.53	0.00	0.00	0.00	0.00	0.00	0.00
6401671	GC008	14.25639	125.23832	0.85m	0.30	2.99	96.71	30.00	55.00	15.00	0.00	0.00	100.00
6401692	GC010	13.40968	124.52107	0.0m	1.67	57.43	40.89	0.00	0.00	0.00	0.00	0.00	0.00
6401693	GC010	14.40968	125.52107	0.9m	0.00	16.80	83.20	20.00	80.00	0.00	0.00	0.00	0.00
6401694	GC010	15.40968	126.52107	1.9m	0.00	11.20	88.80	60.00	40.00	0.00	0.00	0.00	0.00
6401695	GC010	16.40968	127.52107	2.9m	0.27	9.83	89.90	25.00	70.00	5.00	0.00	0.00	0.00
6401664	GC015	13.86932	124.92449	0.0m	9.83	66.76	23.41	0.00	0.00	0.00	0.00	0.00	0.00
6401665	GC015	13.86932	124.92449	0.85m	41.44	32.84	25.72	20.00	55.00	25.00	0.00	0.00	0.00
6401702	GC015	13.86932	124.92449	0.3m	14.70	50.38	34.93	10.00	70.00	20.00	0.00	30.00	70.00

Table 4.3 Sedimentological properties of the gravity cores of the Browse Sea Valley - Kimberley Shelf.

4.7 Core observations and supporting Data

4.7.1 Preface

Here the series of cores are presented with the geochemical and physical data along with an interpretation of the depositional setting. All cores used in this study are gravity cores (GC). This coring method is best used in soft sediments and produces 100mm diameter core, this was split, imaged and described following Geoscience Australia protocols as listed in chapter 3.

4.7.2 Core descriptions

4.7.2.1 Gravity Core 001.

This core is positioned at the northern side of the delta shaped depositional sequence on the northern end of the submerged barrier bar, close to the transition zone of the Browse and Bonaparte Basins. Being west of the Penguin Deeps channel, this area is the entry point for both reworked shelf sediments and terrigenous sourced sediments being transported down the Penguin Deeps Channel and off the Bonaparte Shelf southern margin.

Taken in 130 m water depth, it was in the swash-zone during the LGM. At this time, all sediments would have been mixed and sorted depending on the strength of the climate and oceanographic regimes.

This core top has the lowest CaCO_3 percentage (68%) of all the gravity cores taken for this study. The CaCO_3 values rise down core, to a lower than average, 82% at 1.75m, indicating a relative rise in terrestrial sourced material or marine biogenic silica through time.

The Gravel-Sand-Mud fraction ratios are similar down the core, which indicates a similar deposition regime throughout deposition. The gravel percentage has values between 0.79% and 0.35%, with the gravel at the bottom of the core classified as 95% in an intermediate state of preservation and 5% relict. This reworked shelfal biogenic gravel indicates a higher energy level than that presently experienced.

Sand percentage decreases towards the top of the core by ~7%. 17.9 at 1.75m to 11.5% at the top. The 30 – 40% of the sand down the core was ‘fresh’ in appearance with 50 – 60 % presented in an intermediate state of preservation. Little relict material was observed from this core under the microscope, 60% of the sediment was in an intermediate stage of preservation and 20% for both fresh and relict, indicating at least two provenance sites.

Mud percentage increases towards the top of the core from 81.7% at 1.75m to 84.9% at 1.0m to 87.6% at 0.0m. This rise in relative percentage indicating either an increase in terrestrial sourced material or a reduction of the biogenic sands and gravels.

The core was carbon dated at 1.75m, and an AMS date of 7805 ± 45 years was obtained.

TOC ranged from 0.435 up to 1.501 mid core and back to 0.505% at core top.

4.7.2.1.1 Interpretation

The increase in the mud percentage towards the top of GC 001, also represents a relative increase in the terrestrial sourced material. It is anticipated that mud size

sediments are the only type of terrestrial sourced sediment able to be transported at the prevailing sea levels to this part of the continental shelf. This could also indicate a reduction of biogenic sands and gravels being transported into the deposition site due to their availability or changes in the hydraulic regime. The sandy mud with a less than 1% gravel fraction, indicates a low energy depositional environment throughout its depositional history.

All of the cores are imaged and have the physical and geochemical data along side



Figure 4.4.a CGC 1 Penguin Deep Region.

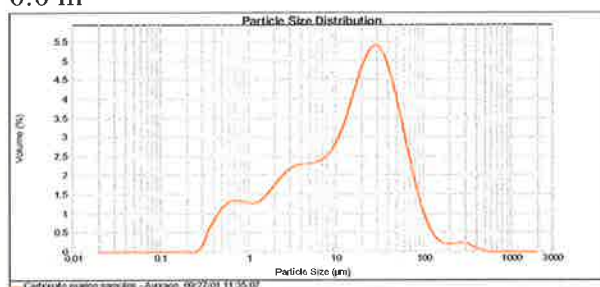
Core length 1.75m

Water Depth 130

Acquisition notes

Penetration 2.6m (includes weights on core head) indicating soft substrate, recovery 1.75m. Base of core grey mud with occasional skeletal fragments, strongly compacted, contains finely divided skeletal grains.

0.0 m



CaCO₃% 68

TOC 0.505

Munsell colour 5y 62

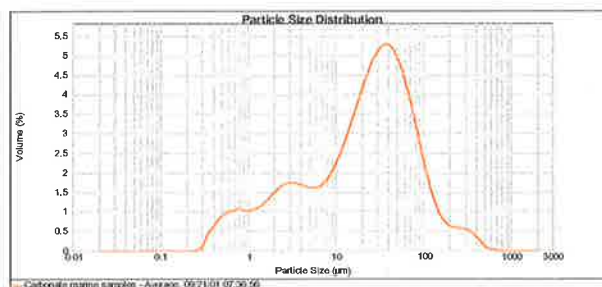
Uniform mud with small % sands

Munsell colour 5y 62



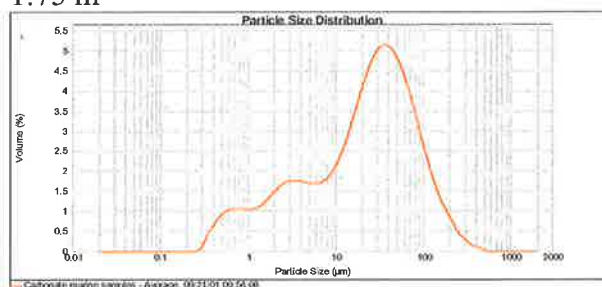
Figure 4.4.b

At 1.0 m



CaCO₃% 75
TOC 1.501
Munsell colour 5y 62

1.75 m



CaCO₃% 82
TOC 0.435
AMS date 7805 (+- 45)
Munsell colour 5y 62

4.7.2.2 Gravity Core 002

This core was taken in 140m water depth (Figure 4.1), within the LGM wave base zone. All sediments therefore have been subject to dynamic hydraulic erosional-depositional, sorting and transport mechanisms of the littoral zone.

Fiscal constraints were such that no carbon dates were obtained from this core.

The relative CaCO_3 percentage decreases from 92% to 74% towards the top of the core, indicating one of two things. Either there was a decrease in the carbonate sediment reaching the deposition zone or there was an increase in the terrestrial component being deposited.

The gravel component of the core steadily decreases from 13.979 at 1.8m to 2.9793 at 0.0m. Yet the sand percentage fluctuates down core (Table 4.4).

Depth	0	0.85	1.5	1.85
Sand %	33%	46%	30%	36%
Mud%	63%	47%	62%	49%

Table 4.4 Depth Sand and Mud Percentages of core GC 002

The mud fraction has two distinct relative increases corresponding with the variations in sand percentages (Table 4.4). The TOC% almost doubles, rising from 0.235 at core base to 0.460% at the core top.

The sediments vary from a mud-sand-gravel mix to a mud-dominated sample to an equal, muddy-sand mixture back into a mud-dominated deposit. This indicates that pulses of a higher energy depositional regime occurred at 0.85m and at 1.8m core depth.

4.7.2.2.1 Description

The gravel component of the core steadily decreases underlying a general low grade fining up sequence. The sand fraction ranges from 46.526 to 30.056 % but not in a linear relationship through the core. This represents a pulse of sand at 0.85m at 46.526 %. And the CaCO_3 % steadily declines towards the top of the core independently of the mud or sand %. The changes in sand % could be interpreted as resulting from the passage of regional storms or that energy was higher during the Mid Holocene.



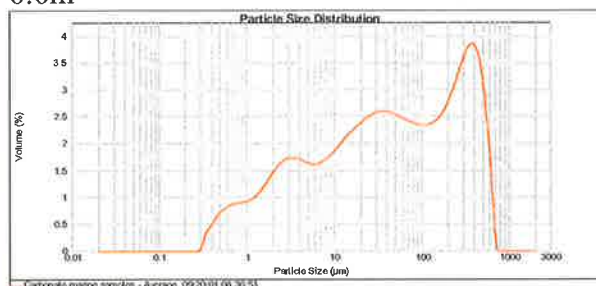
Figure 4.5.a GC 2 Penguin Deeps Region.

Core length 1.85m Water depth 140

Acquisition Notes

Base of core – Grey fine sandy mud, vagrant bryozoans, large bivalve, gastropods, benthic forams, lots of angular skeletal grains, glauconitic peloids (1-2%).

0.0m



0.0 m

CaCO₃% 74

TOC 0.460

Munsell colour 5Y62

Uniform colour to 86 cm depth

0.85 m

CaCO₃% 87

TOC 0.314

0.85 m large undetermined biogenic nodule removed

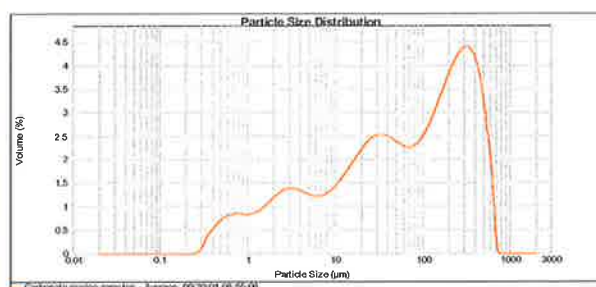
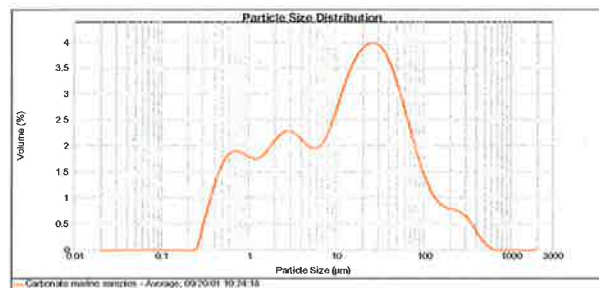




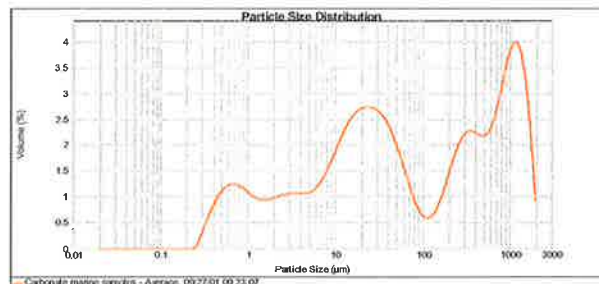
Figure 4.5.b
Core becomes dappled
Munsell colour 5Y61

1.5 m

Munsell colour 5Y52
 $\text{CaCO}_3\%$ 94
TOC 0.276



1.8 m $\text{CaCO}_3\%$ 92 TOC 0.235



Bottoms out on a barnacle substrate (intertidal remnant?).

4.7.2.3 Gravity Core 003

This core, taken in 134 m water depth at the top of the Browse Sea Valley, would have been within the wave base at -144m during the LGM and subject to the littoral and hydrological regimes at that time.

Like most of the cores in this area, there is a reduction in the CaCO_3 % in the sediments towards the top of the core, ranging from 90% at 1.8m, 81% at 0.8m and 75% at 0.0m (Table 4.5).

Depth	0	0.8	1.8
$\text{CaCO}_3\%$	75	81	90
Gravel %	<1	<1	<1
Sand %	36	39	56
Mud %	63	60	43

Table 4.5 CaCO_3 Gravel Sand and Mud Percentages of Core GC 003

The gravel percentage is insignificant, with all values below 1%, yet the sand % component of the core reduces and the mud % increases correspondingly (Table 4.4).

Microscope analysis of the sand component indicates a mixture of fresh, intermediate and relict sediments, with the dominant component being the intermediate sands (65%) then fresh sands (30%) and relict sands (5%), for the majority of the core.

AMS C^{14} dates show an accumulation of 1.8m of sediment over 5257 years, if accumulation equals deposition, then a whole core deposition rate of 3.424 cm/ky can be calculated. This rate changes over time, the upper 0.8 m, having a rate of

1.682 cm/ky and the lower 1m, a rate of 19.92 cm/ky, indicating a significant decrease of over ten times in accumulation rates in the later stages of deposition. The CaCO_3 % decrease from 90 – 75%, suggests a relative rise in terrestrial inputs over the time represented by deposition of this core. The grain size data demonstrates a shift from a sandy mud, to a muddy sand at 7723 years. This type of texture was maintained thereafter.

TOC almost doubles from 0.236 % at the base of the core to 0.438 % at core top.

4.7.2.3.1 Interpretation

The colour of the sediments of this core suggests a uniform deposition regime with no major depositional textural variations. Post depositional bioturbation has occurred throughout the core yet more so, towards the top of the core and may indicate a slowing of the deposition rate due to the potential re-suspension of sediments into the water column. This bioturbation is also responsible for the coarsening up of the sediment towards the top of the core. The slowing in the deposition rate is confirmed with the AMS dates with the first 0.8 m being deposited in ~500 years and the second 0.8m being deposited in 4755 years. This may be due to faster erosional rates at the beginning of the Holocene, envisioned as the SL inundated the shelf and began removing the shelf sediments and depositing them here in the Browse Sea Valley.



Figure 4.6.a GC 3 Penguin Deeps Region.

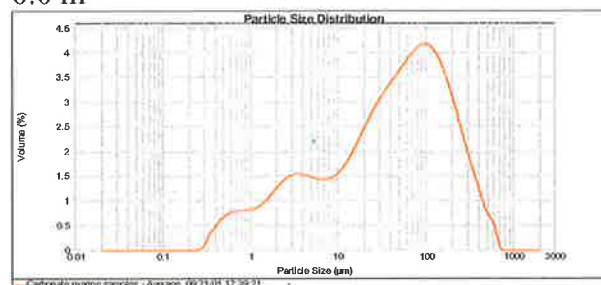
Core length 1.82 m

Water depth 133

Acquisition Notes

Base of core – Grey mud, very fine grained, compacted, angular skeletal material, benthic forams, gastropods, bryozoans, glauconitic peloids (2%), penetration 2.2m, recovery 1.82m.

0.0 m



CaCO₃% 75

TOC 0.438

AMS Date 2968.0 +/- 40

Highly bioturbated

Numerous bivalves ranging in size from 0.5 - 3cm

Uniform Munsell colour 5Y52

CaCO₃% 81

TOC 0.312

AMS Date 7723.0 years +/- 45

0.8 m





Figure 4.6.b
At 82 cm abundant small bivalves

Uniform Munsell colour 5Y52

Bioturbation throughout
Burrows in-filled with sand

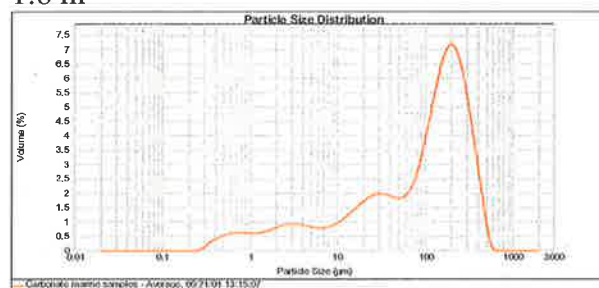
Reduced bioturbation

CaCO₃% 90

TOC 0.236

AMS Date 8225.0 $\pm$ 60

1.8 m



4.7.2.4 Gravity Core 004

GC 004 (Figure 4.1) was acquired in 202 m water depth and has a total penetration of 0.58m, the shortest core taken. The $\text{CaCO}_3\%$ value has a small reduction, reduces from 84% at the base to 82% at the top of the core. This follows the trend of most other cores. The gravel and mud percentages are both reduced by 2% and 12% respectively towards the top of the core. The sand fraction increases by 14% from 73 to 87%, the highest sand percentages in all of the cores yet in one of the deepest water depths. No AMS C14 dates were acquired for this core.

This is a coarsening-up sequence, changing from a sandy mud to a more sand dominated deposit. TOC values rise, from 0.132 % at the core base, to 0.189 % at the core top.

4.7.2.4.1 Interpretation

This could be inferred as a storm deposit, with the sand component being shelfal sands re-deposited off the shelf, perhaps due to energy from a cyclone or intense low pressure. It is possible that this is from one cyclone or could be from a series of back-to-back storms.



Figure 4.7. GC 4 Penguin Deeps Region.

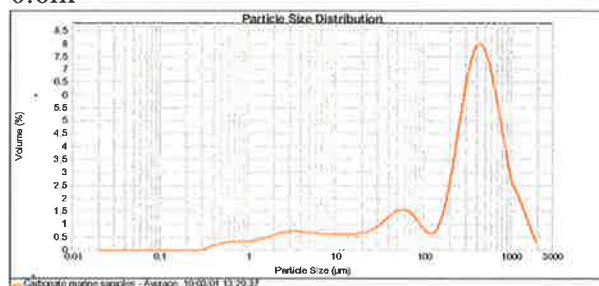
Core length 0.60m Water depth 202m

Acquisition Notes

Penetration 0.6m, recovery 0.6m, biogenic sand, water washed core. Grey sand, medium grained, mod sorted, mixture of abundant planktic and benthic forams, sub-angular skeletal fragments, rare 1-2mm skeletal debris

Oxidised top of core 5Y31

0.0m



CaCO₃% 82

TOC 0.189

20 cm 5Y52

40cm 5Y61

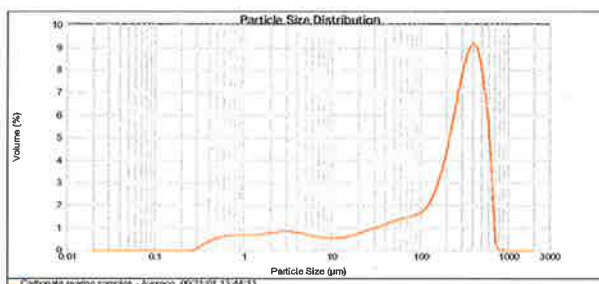
Band of lighter sediments at 42 - 46 cm depth

Munsell colour 5Y71

0.58m

CaCO₃% 84

TOC 0.132



60 cm 5Y61

4.7.2.5 Gravity Core 005

This core acquired at 191 m water depth (Figure 4.1), at 4.57m in length it is the longest gravity core taken during the survey. This core showed uniform sediment colour and texture throughout core samples. CaCO_3 values vary throughout the core from 90 – 83%.

There are only two samples with ‘fresh’ gravels and these are found mid core, intermediate preserved gravels are more abundant and range up to 75 %. The sediments show several episodes of coarsening up from a muddy sand to a sandy mud, throughout the core (Table 4.6). The TOC values average at 3.18 (Appendix 3.1), and show a slight increasing overall trend, but no association was apparent when contrasted against other geochemical or physical properties.

4.7.2.5.1 Interpretation

The variation of CaCO_3 and textural parameters in this core does not correlate with any size / geochemical relationships as encountered in the other cores. There is variation of the CaCO_3 values in this core (Table 4.6) which are unrelated to mud fraction percentages as seen in other cores. This could indicate that there is no linear relationship with grainsize and geochemistry or that the geochemical values are affected by a small quantity of sediment.

Depth down core	0	0.7	1.55	1.7	2.52	3.05	3.6	4.57
CaCO_3	83	90	89	86	89	83	84	88
Gravel %	1.2	1.4	1.0	1.1	4.2	1.7	2.4	4.0
Sand %	73.4	34.5	40.0	29.7	51.3	42.9	58.0	49
Mud %	25.3	64.0	58.9	69.0	44.4	55.3	39.59	46.9

Table 4.6 CaCO_3 Gravel Sand and Mud Percentages of Core GC 005



Figure 4.8a GC 5 Penguin Deeps Region.

Core length 4.59 m Water depth 191 m

Acquisition Notes

Base of core – light grey muddy sand, common skeletal clasts (1-2mm), fine-medium grained, mod sorted, bivalves, benthic and planktic forams, minor glauconitic peloids (2%), gastropods, sub-angular skeletal fragments (65%), large broken bivalve fragments.

Friable sediments for up to 30cm depth uniform Munsell colour 5Y52

0.0 m

CaCO₃% 83

TOC 0.315

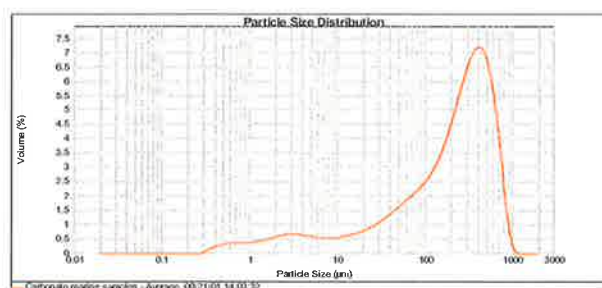
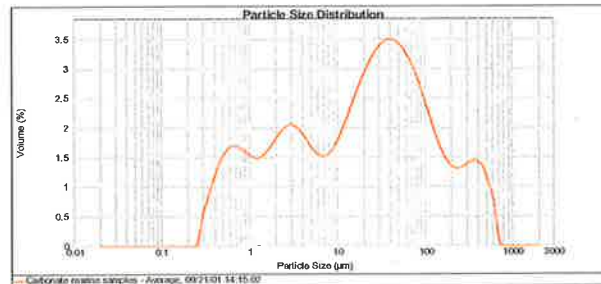




Figure 4.8.b
61 cm
Munsell colour 5Y52

0.7 m

CaCO₃% 90
TOC 0.404



1.40 m depth
Munsell colour 5Y62
1.55 m
CaCO₃% 89
TOC 0.302

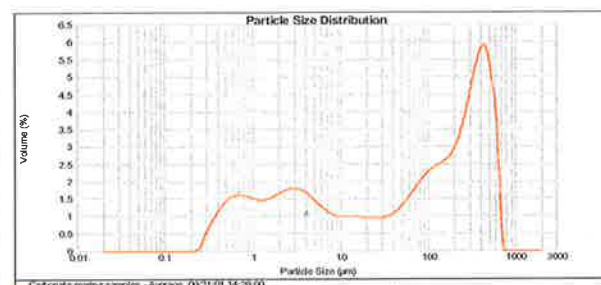




Figure 4.8.c 1.61m

1.7 m
 $\text{CaCO}_3\%$ 86
 TOC 0.301



1.9 m
 Munsell colour 5Y62

2.05 large bivalves (4cm size) and flat echinoderms

2.52 m
 $\text{CaCO}_3\%$ 89
 TOC 0.351

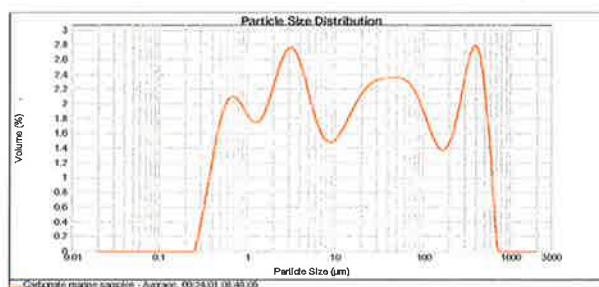


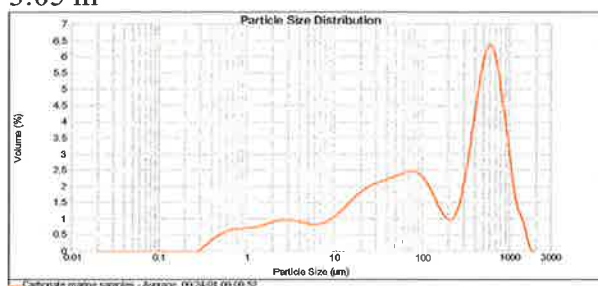


Figure 4.8d
2.61 m
Munsell Colour 5Y62

2.90 m
Munsell colour 5Y62

3.05 large bioclasts across core
CaCO₃% 83
TOC 0.331

3.05 m

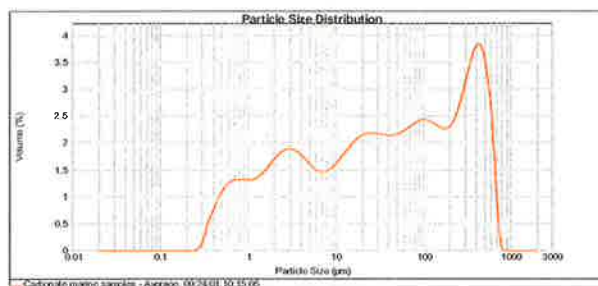


Colour patches
Mud clasts

Munsell colour 5Y52
3.55 m

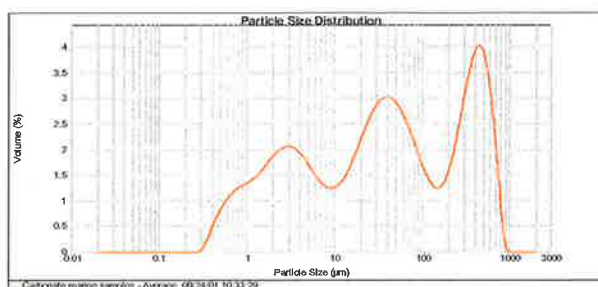


Figure 4.8.e
3.6 m Munsell colour 5Y52
CaCO₃% 84
TOC 0.310



3.7 m
Munsell colour 5Y62

4.57 m
CaCO₃% 88
TOC 0.230



4.59 m, Munsell Colour 5Y62 Large bioclasts in a uniform coloured sediment.

4.7.2.6 Gravity Core 007.

Acquired in 205m water depth, this 2.1m core (Figure 4.1) is one of only two cores that also show a CaCO_3 % increase, up core, from 84% – 90%.

Sediments generally represent a fining-up sequence, from a muddy sand to a sandy mud, with some coarser material towards the top of the core. The pale khaki coloured sediments become increasingly coarse, and increasingly bioturbated, at the bottom of the core. Gastropods appear to be found in life position at 0.6 and 0.2m, down core. Grain size distribution is 7% gravel, 63% sand and 30% mud, whereas the top of the core is 3% gravel, 17% sand and 80% mud, yet the change in CaCO_3 % is only 6%.

4.7.2.6.1 Interpretation

This core shows a range of sediment inputs, with bioturbation removing some of the fabric, yet there are several swirling mud clasts throughout the core that give textural variation, perhaps representing movement of nearby fine-grained plastic sediments into the deposition zone. Storms or slope failure give rise to this type of textural variation, as it is proximal to the steep inter-basin transition zone and adjacent to shelf slope sediments. The sediment fabric indicates a lessening of depositional energy since the initial deposit. Gastropods in life position may have been inundated with sediments and due to this sudden input, expired.



Figure 4.9a GC 7 Penguin Deeps Region.

Core length 2.1m Water depth 205

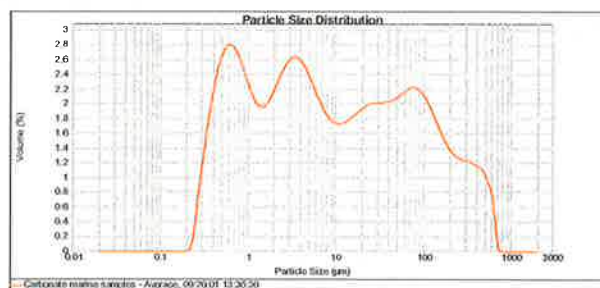
Acquisition Notes

Top of core: Grey sandy mud, well sorted, abundant skeletal debris, burrows in substrate. Bottom of core: grey medium to coarse grained muddy sand, abundant skeletal debris, rare skeletal clasts 1-2mm, pteropods, planktonic and benthic forams (60:40), vagrant bryozoan, textuliria forams, common glauconitic peloids, moderately sorted.

0.0 m

CaCO₃% 90

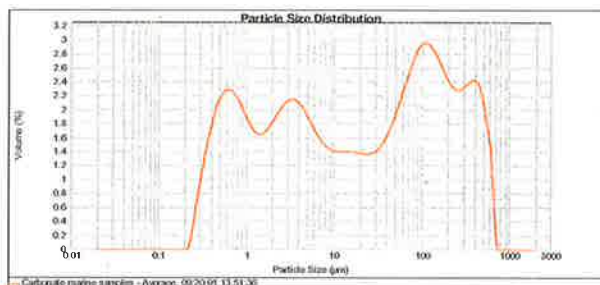
TOC 0.300



0.4 m

CaCO₃% 90

TOC 0.360



1.05 m

CaCO₃% 84

TOC 0.401

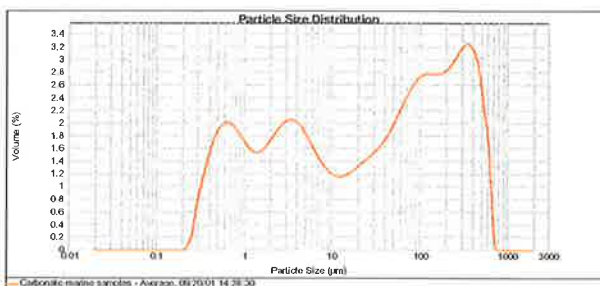




Figure 4.9b

1.1 m 5Y71 uniform colour with some slight variation; lighter patches textural change

1.12 m gastropod, 3cm in length

1.2 m echinoderm clasts

1.27 m. Increased bioturbation and circular mud clasts to 5cm diameter

1.35 m. Colour change associated with mud clasts

1.45 m Shell hash zone

1.48 m Increased bioturbation

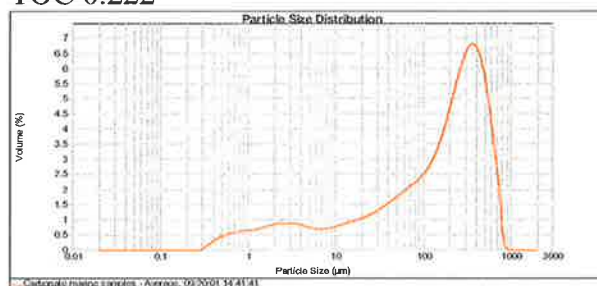
Circular mud clasts

1.7 m Textural change with more intense bioturbation introducing larger size sediment grains

2.07 m

CaCO₃% 84

TOC 0.222



2.1 m Bottom of core

4.7.2.7 Gravity Core 008

This is a short gravity core of 0.85m taken in 157m water depth. The second of two cores with an increase of CaCO_3 towards the top of the core, in this case a rise of 1%. The gravel percentage value reveals a major textural change at 0.6m (down core) from a sandy mud to a highly bioturbated shell hash and mud with clasts. The first gravel percentage changes from 0.3 % at 0.85m to 22% at the top, sand varies from 3% at the bottom to 63% at the top and mud reduces from 96% at the bottom to 16% at the top. TOC values drop by almost one half, from 0.233% to 0.128%.

4.7.2.7.1 Interpretation

This depositional sequence is indicative of a storm deposit, with a sudden influx of coarse sediment into an otherwise quiet lightly bioturbated deposition zone. The dramatic variation in deposition style is readily seen in the core, as a sudden linear textural and colour change at 0.6m core depth.



Figure 4.10a GC 8 Penguin Deeps Region.

Core length 0.95m Water depth 157

Acquisition Notes

Pale grey sandy mud, medium grained, skeletal grains are common.

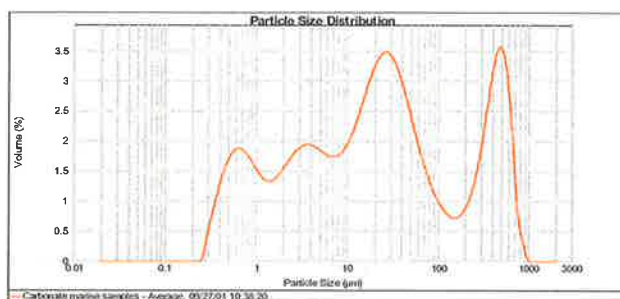
Munsell colour 5Y63

This core is highly bioturbated
bivalve shell hash / much in life position for the top
65 cm.

0.0 m

CaCO₃% 94

TOC 0.128



0 – 0.5m Mud with bio clasts

0.5 – 0.6 m Shell hash

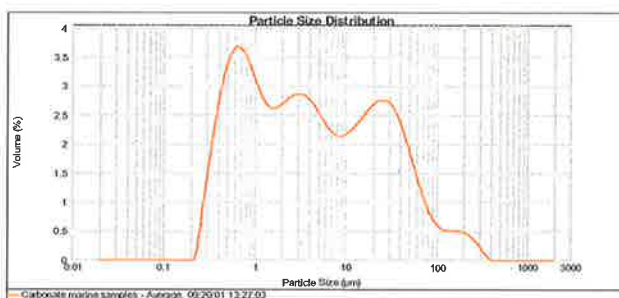
0.60 m Change to muds reduced bioturbation

0.65 m Munsell Colour 5Y62

0.85m

CaCO₃% 93

TOC 0.233



base sits on a soft muds Munsell colour 5Y71

4.7.2.8 Gravity Core 10

This core was acquired from 117m water depth (Figure 4.1). It was in the swash-zone during the LGM when all sediments were mixed and sorted, depending on the strength of the sediment inputs and oceanographic regimes. This core is dominated by mud with the exception of a core top of sandy mud (Table 4.7). The CaCO₃ % of this core reduces towards the top of the core, from 83% up to 84% at 1.9 m and 0.9 m respectively and down to 81% at 0.0m. This core represents a coarsening-up sequence with minimal gravel but a strong trend from mud to sand (Table 4.7). This indicates a textural coarsening-up during the last 0.9m of deposition. This change has been dated to have occurred between 9155 – 5066 AMS Carbon¹⁴ years (Table 4.7).

Depth	0	0.9	1.9	2.9
CaCO ₃	81	84	84	83
Gravel	1.6	0	0	0.2
Sand	57.4	16.8	11.2	9.8
Mud	40.8	83.1	88.7	88.9
C14 Dates	5066	9155	11432	11880

Table 4.7 CaCO₃ Gravel Sand and Mud Percentages with AMS Dates of Core GC 005

The core yields the oldest AMS date in the study, of 11880.0 ± 55 . Accumulation rates for the deepest part of the core from 2.9m to 1.9m are the fastest in the study with 22.32cm/ky from 11880 – 11432 years. From 1.9 to 0.9 m depth in the core, deposition rates are slower at 4.39 cm/ky and from 0.9 to 0 m are slowest at 2.2 cm/ky. TOC steadily reduces throughout the core from 0.408 % at the bottom to 0.307 at the core top.

4.7.2.8.1 Interpretation

The coarsening up sequence over the length of this core appears to take place sequentially. Fine grained uniform sediments accumulate initially at 22.32 cm/ky. Sedimentation slowed to 4.39 cm/ky, yet the sediments appear to remain the same in makeup and texture. Bioturbation is apparent after this, increasing particularly from 1.9 to 0.9 m core depth. Later, a different depositional regime began to dominate with the deposition of larger grained sands. Microscope analysis revealed that these have both fresh and intermediate components. These sands are also apparent in the bioturbated burrows. The change in the texture of the more recent sediments could result from storm energy. In summary, this core could be interpreted as a low energy deposition centre within range of storm input.



Figure 4.11a GC 10 Penguin Deeps Region.

Core length 2.90 m Water depth 117.2

Acquisition notes

Bottom of core: Fine grained muddy sand, poorly sorted, (3-5%), abundant angular skeletal clasts, rare skeletal rods.

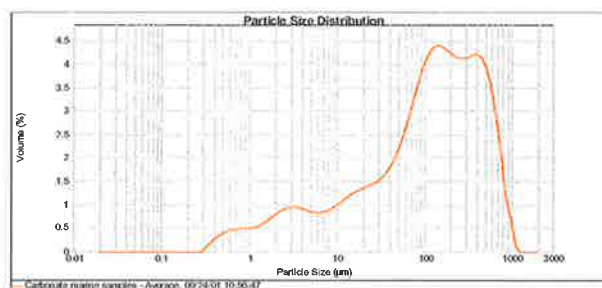
0 m

CaCO₃% 81

TOC 0.307

AMS Date 5066.0 +/-40

Munsell colour 5Y63 Sandy Biogenic sediment



0.40 m

Munsell Colour 5Y62

0.68 change to increased muds

burrows through the mud is in-filled with sand

0.85 m 5Y61

0.90 m

CaCO₃% 84

TOC 0.328

AMS Date 9155.0 +/-50

Uniform colour, 5Y 62 and bioturbation throughout

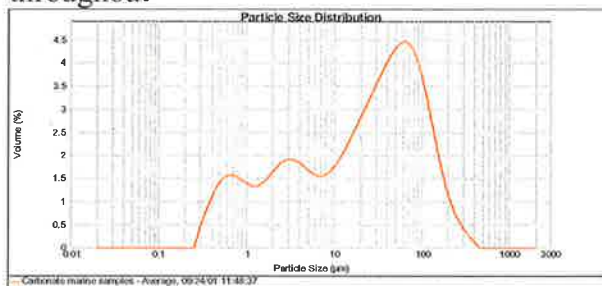
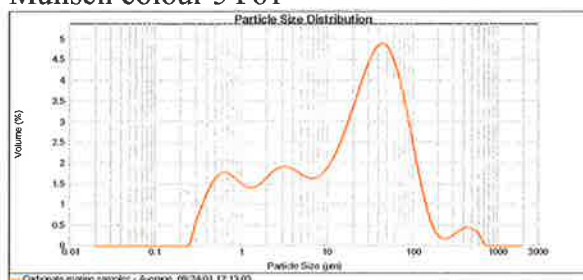




Figure 4.11.b 1.90m
 $\text{CaCO}_3\%$ 84
 TOC 0.359
 AMS Date 11432.0 $\pm$ 55
 Munsell colour 5Y61



Below this there is reduced bioturbation,
 uniform colour and texture 5Y62

Uniform colour 5Y62 and textured sediments

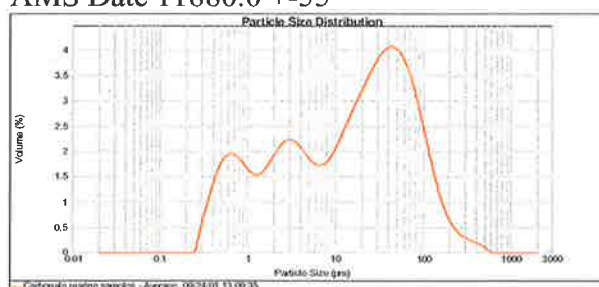


Figure 4.11.c

Uniform colour 5Y62 and textured sediments

Uniform colour 5Y62 and textured sediments

2.9 m
CaCO₃% 83
TOC 0.408
AMS Date 11880.0 ±55



4.7.2.9 Gravity Core 015.

GC 015 was acquired at 64m water depth on the Kimberley Shelf headland (Figure 4.1), slightly to the south of the main study area and represents a control site. This core bottomed out on a CaCO_3 crust. Both top and bottom of the 0.85m core were AMS C14 dated to give an overall sediment accumulation rate. The CaCO_3 values of bulk sediment ranged from 87% at the bottom of the core to 83% at the core top.

GC 015 has a texture quite different compared to the other cores. It was full of molluscs, worm tubes both scattered and in apparent life position along with other large size biogenic clasts. Gravel decreased from 41% to 14% at 0.3m to 19% at the top, and the sand, 32% at 0.85m 50% at 0.3 and 67% at the top and mud was fairly constant between 23 – 35% yet some of the sediment analysis is not characteristic. This may be due to the large biogenic carbonate clasts being excluded from the grain size analysis.

The deepest part of the core is a gravel 41% sand 33%, mud 26% mixture, which passes into a muddy-sand up core, interbedded with large bioclasts. This could be interpreted as a fining up sequence from a hard substrate.

Due to its location away from the Penguin Deep, this area did not receive the amount of reworked shelf sediments which are encountered at the deposition centre of the Penguin Deep Fan. Here, the whole core accumulation rate is 17.14 cm/ky

TOC ranged increased from 0.099% at the bottom of the core to a core top value of 0.161%.

4.7.2.9.1 Interpretation

The sediment age indicate that the have been accumulating for the past 4959 C¹⁴ years, with an accumulation rate of 17.14 cm/ky. This may be affected by the adjacent hydrocarbon seeps (O'Brien et al 2002). Many large bioclasts in various states of preservation, some bored, others encrusted or in life position, indicate an ecologically vibrant deposition site.

This site on the Kimberley Shelf headland does not have the quantity of fine sediments seen in the other cores within the Penguin Deeps Fan. The sediment texture and depositional structure of the core indicate that the more diverse and larger bioclasts within the core the more likely the core is proximal to a diverse biogenic reefal environment.



Figure 4.12.a GC 15 Penguin Deeps Region.

Core length 0.85 m Water depth 66

Acquisition Notes

none

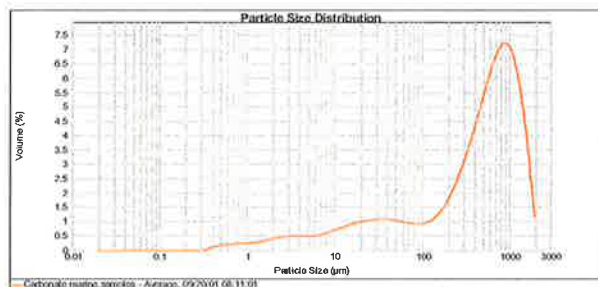
0.1 m Oxidised top sediments

GC015 0.0cm

CaCO₃% 83

TOC 0.161

AMS Date 3181.0 ±40



0.3 m

CaCO₃% 88

Change to more large bioclasts at 0.35m

0.4 m Slightly dappled

0.6 m Worm tube

Molluscs 10cm

Munsell colour 5Y61

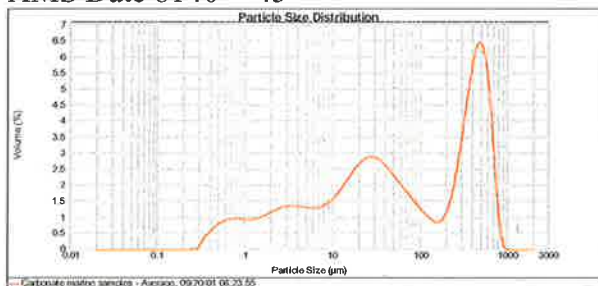
Coral and bioclasts

0.85 m

CaCO₃% 87

TOC 0.099

AMS Date 8140 ±45



Munsell colour 5Y61

Core stops on lithified crust, 1cm thick HRDZ?)

Chapter 5 Bathymetric and Sub bottom profiles of the Kimberley Shelf and the Browse Sea Valley.

5.1 Introduction

This chapter describes a new bathymetric and sub bottom profiles (Figure 5.1, 5.2) across the Kimberley Shelf, and, utilising also data described earlier in the thesis, provides a more detailed explanation and interpretation for the terraced shelves of Northwest Australia than has previously been accomplished.

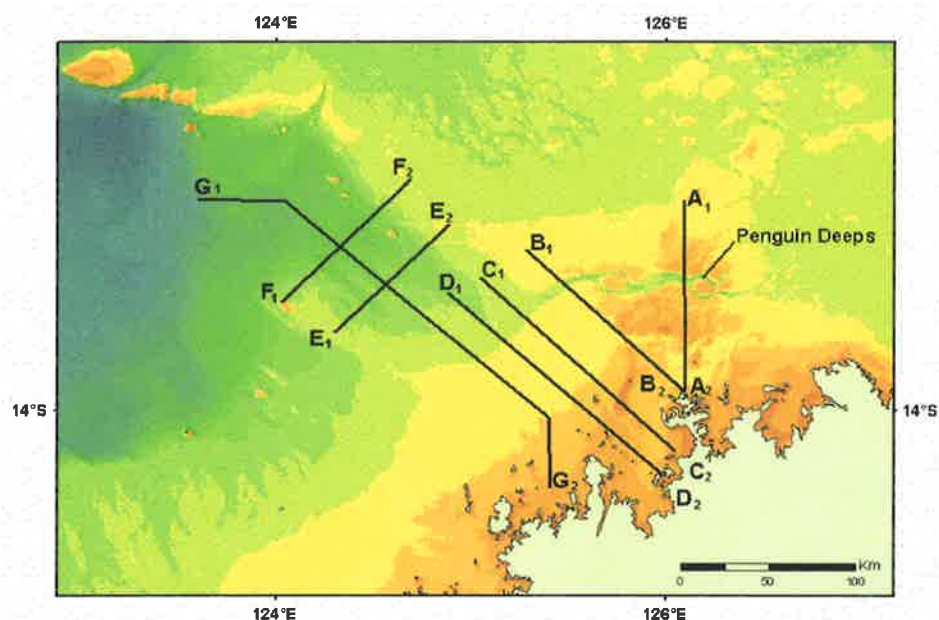


Figure 5.1 The bathymetric profile lines across the study area.

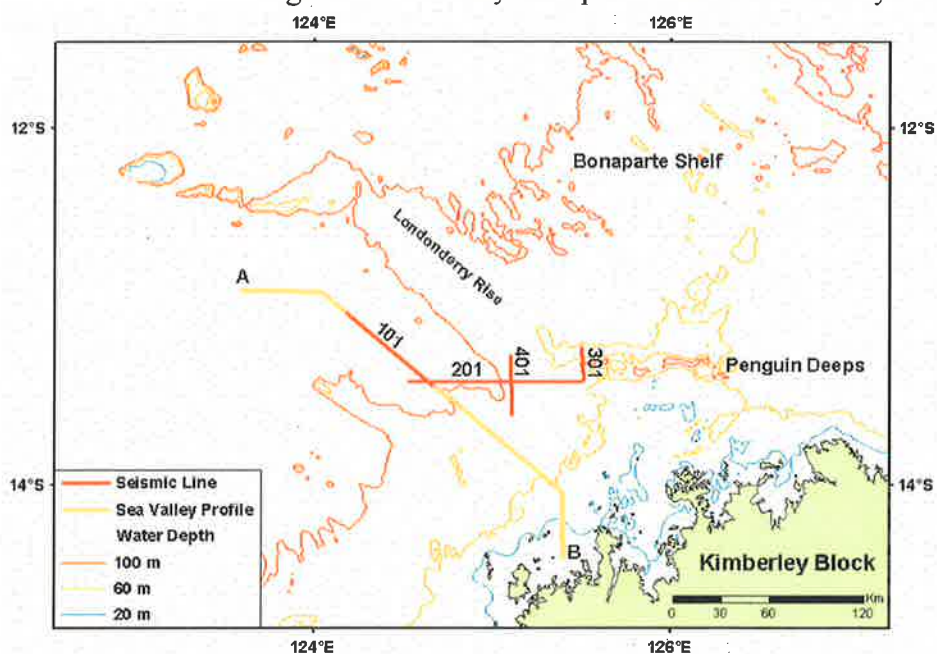


Figure 5.2 Seismic acquisition and profile location.

5.2. Bathymetry Methods

By utilising the Geoscience Australia bathymetric data base, a series of profile lines have been plotted for this study allowing better identification of a range of sea floor features (Figure 5.1). These seven bathymetric lines (A-G) cover the area where sediments samples and sub bottom profiling has been acquired for this study.

5.3 Bathymetric Results

The distinct bathymetric features have been identified, such as the series of terraces across the shelf, the 'lip' on the Londonderry rise. Whereby a new level of detail introduces an enhanced understanding of the spatial relationship with the overall shape of the Browse Sea Valley, Penguin Deeps and the range of sea floor features.

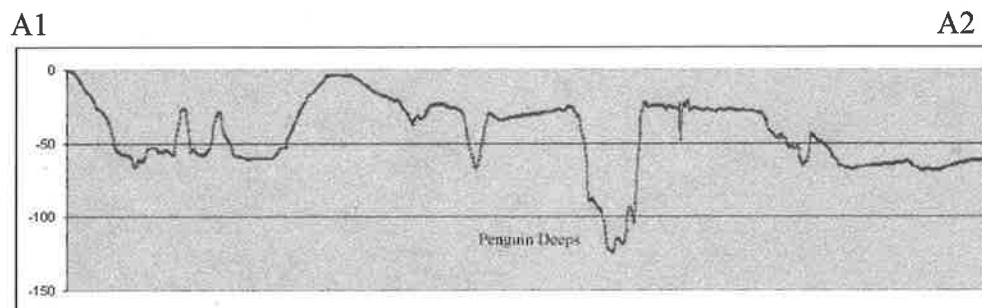


Figure 5.3 Profile 'A' north across the Kimberley Shelf and Penguin Deeps.

Profile 'A' (Figure 5.3) runs due north from the tip of Cape Bougainville (Figure 1.1), across the inner shelf, through the Penguin Deeps and onto the northern side of the channel near the western end of the Greater Londonderry Rise (Figure 1.1).

B1

B2

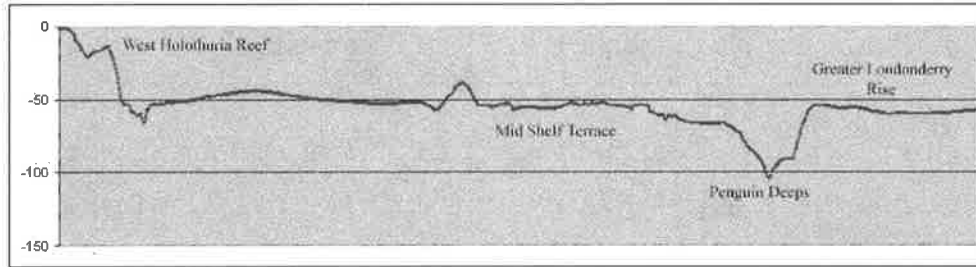


Figure 5.4 Profiles D across the Kimberley Shelf

The 'B' profile (Figure 5.4) extends from the tip of Cape Bougainville on a northwest path, through the Penguin Deeps and onto the Greater Londonderry Rise. The small rise near the shallow end of the profile is associated with West Holothuria Reef. The undulating inner - mid shelf terrace at $50\text{m} \pm (10\text{m})$ WD continues out to the fall, associated with the Penguin Deeps. This depression leads into the Penguin Deeps proper, and then across to the other side of the channel. The northern side of the channel is higher than the southern side and a topographically positive feature is noted at the abrupt change in topography at the northern cliff face of the Penguin Deeps.

C2

C1

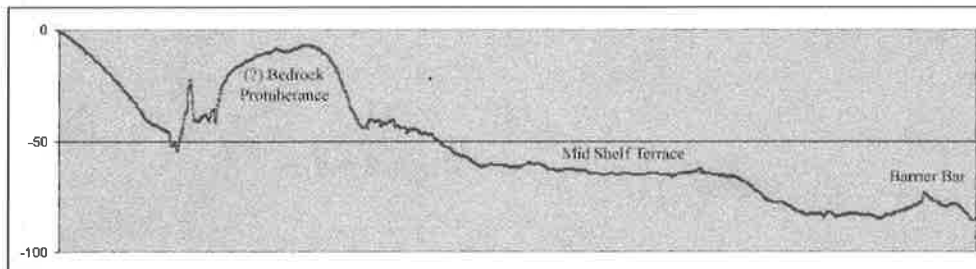


Figure 5.5 Profiles D across the Kimberley Shelf

Profile 'C' (Figure 5.5) tracks northwest from Admiralty Gulf (Figure 1.1) across to the north side of the Penguin Fan. The near shore rises are probably bedrock protuberances which used to be islands like their spatial related counter parts. The profile crosses the mid shelf terrace and dips down towards the head of the

Browse Sea Valley at the terminus of the Penguin Deeps channel. The slight rise near the end of C1 is the rise associated with the 'barrier bar', and it dips away on the other side of this feature.

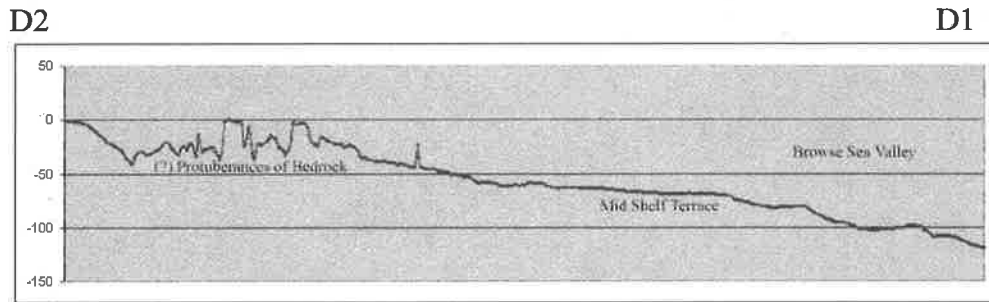


Figure 5.6 Profiles D across the Kimberley Shelf

Profile 'D' (Figure 5.6) starts on one of the islands just off shore within the Admiralty Gulf and crosses several other small islands which are thought to be protrusions of Proterozoic bedrock. These islands are encircled by the inshore sediment prism (ISP), the profile continues across the inner shelf terrace at ~40m water depth (WD) and leads out to the mid shelf terrace (60 – 80m WD) in a north-westerly direction.

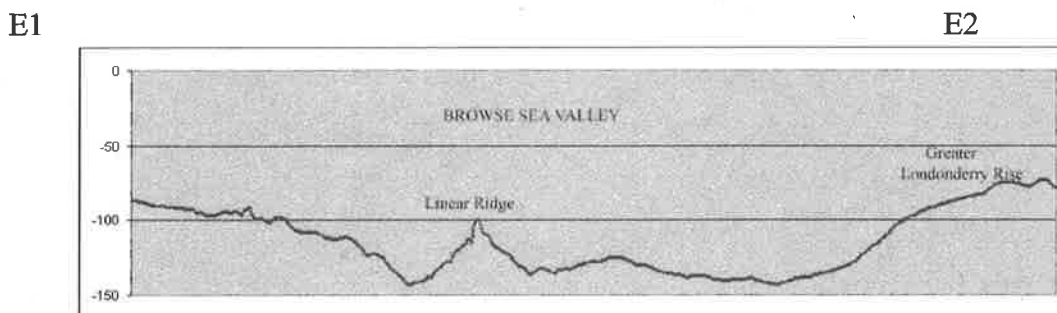


Figure 5.7 Profile E across the outer Browse Sea Valley

Profile 'E' (Figure 5.7) across the inner Browse Sea Valley, helps define one of the distinct linear ridges running parallel with the Greater Londonderry Rise and the topographical high ridge associated with the Heywood Shoals (Figure 1.1).

F1

F2

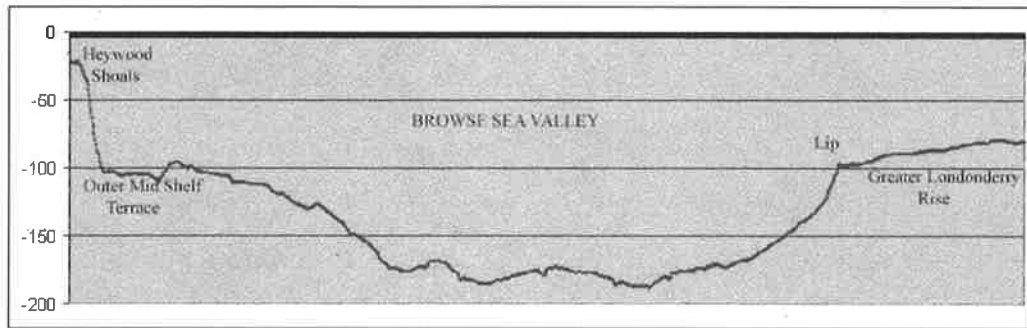


Figure 5.8 Profile F across the outer Browse Sea Valley

Profile 'F' (Figure 5.8) the outermost profile of the Browse Sea Valley, highlights Heywood Shoals (F1) the distinct outer mid shelf terrace, the valley itself, and Greater Londonderry Rise. The 'lip' on the edge of the shelf break, this topographical positive feature of 1.5m, delineates the edge of the Greater Londonderry Rise and may indicate reef growth as times of rising sea levels.

G1

G2

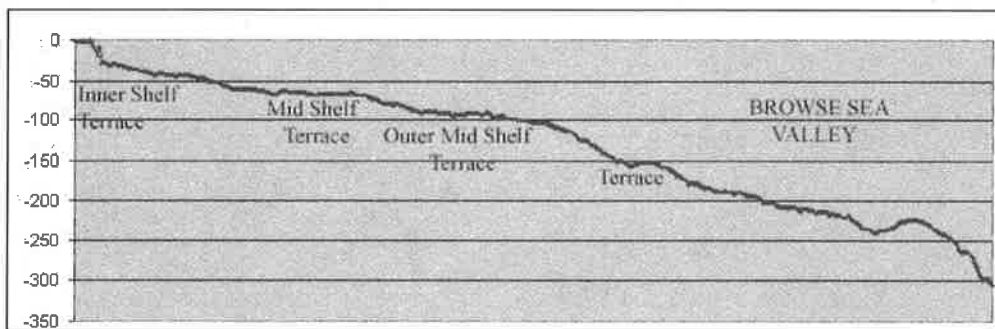


Figure 5.9 Profile 'G' through the Browse Sea Valley.

Profile line 'G' (Figure 5.9) starting from within the Montague Sound (Figure 1.1), tacks north to the 60m bathymetric line. From here it tracks NW inn line with the Browse Sea Valley and then tracks westwards into deeper water. Main features of this profile include the inner shelf terrace, the mid shelf terrace, the outer mid shelf terrace, a terrace at 150m. The line follows the sea valley out to depths of greater than 300m.

5.4 Sub-bottom Profiling Equipment and methods:

The sub-bottom profiling source was an ORE Model 5813A Acoustic Source, commonly referred to as a Boomer. This was driven by a Geopulse 5420A power supply. A Teledyne 4 channel streamer was used, giving an overall active array length of 25 meters. The acquisition system was a Geoacoustics SE881 Sonar Enhancement System. The shot interval was 2.43 seconds with the recording bandwidth set at 100Hz to 5kHz. Four lines of sub-bottom profiles were collected a total of 231.2 line-km (Figures 5.10, 5.11, 5.12, 5.13). These provided a range of useful penetration of <100m and a resolution of up to 10m.

Four lines sub bottom profiling were undertaken for this study (Figure 5.2).

1. On a SE NW trend, down the centre of the Browse Sea Valley. Line 101.
2. Perpendicular to the barrier bar. Line 201
3. Across the Penguin Deeps channel. Line 301
4. In line with, and across the barrier bar. Line 401

Major depositional events were easily identified from these seismic images. While there are no age constraints awarded to them, a depositional order has been established. Sediment packet profiles indicate of they have been deposited during a rising falling or steady relative Sea Level (Figures 5.10 – 5.13 and enclosures 5.1 – 5.4). These interpreted images use thicker lines to denote sequence boundaries and thinner lines of the same colour, to identify events within the depositional sequence.

Line 101

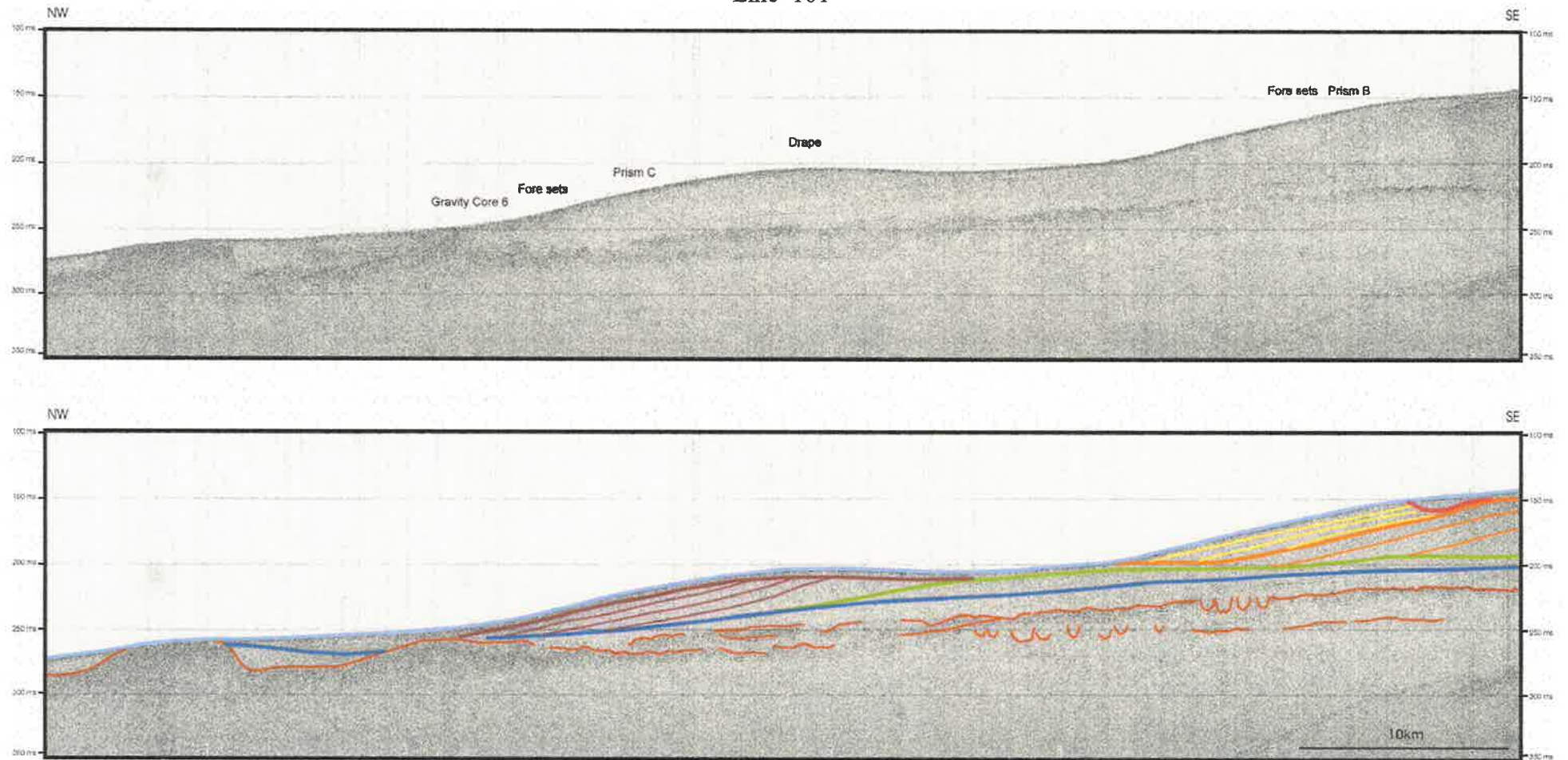


Figure 5.10 The annotated bathymetric profile (top) and the interpreted sub bottom profile of line 101 (bottom)

Line 201

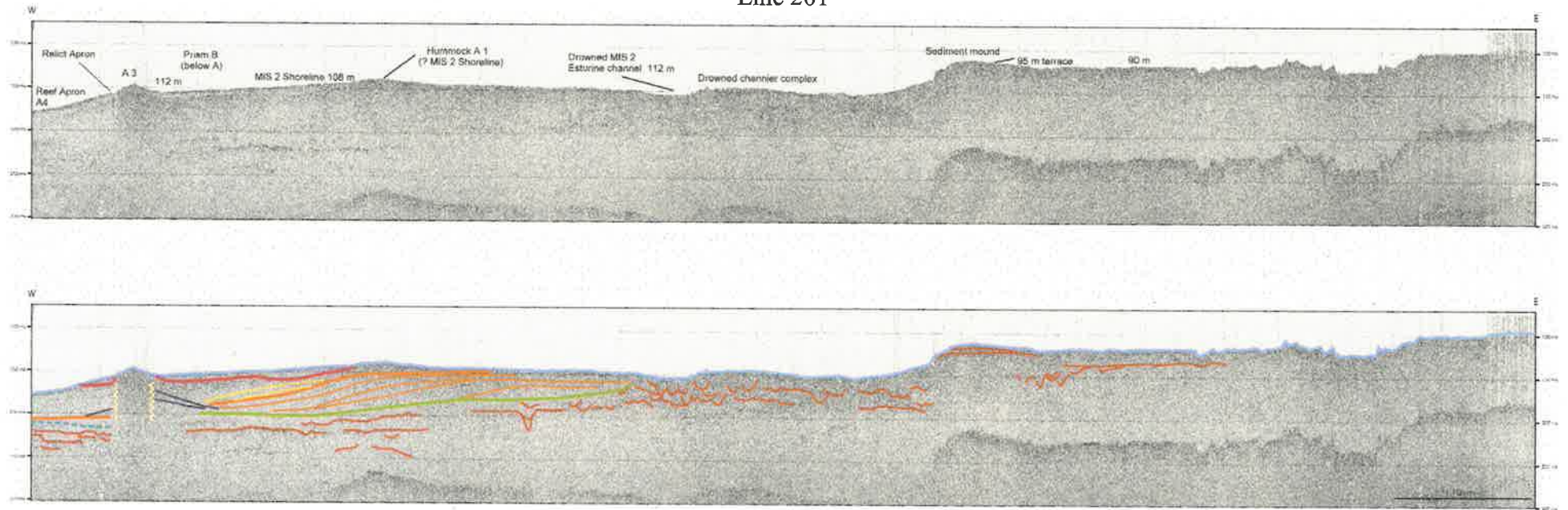


Figure 5.11 The annotated bathymetric profile (top) and the interpreted sub bottom profile of line 201 (bottom)

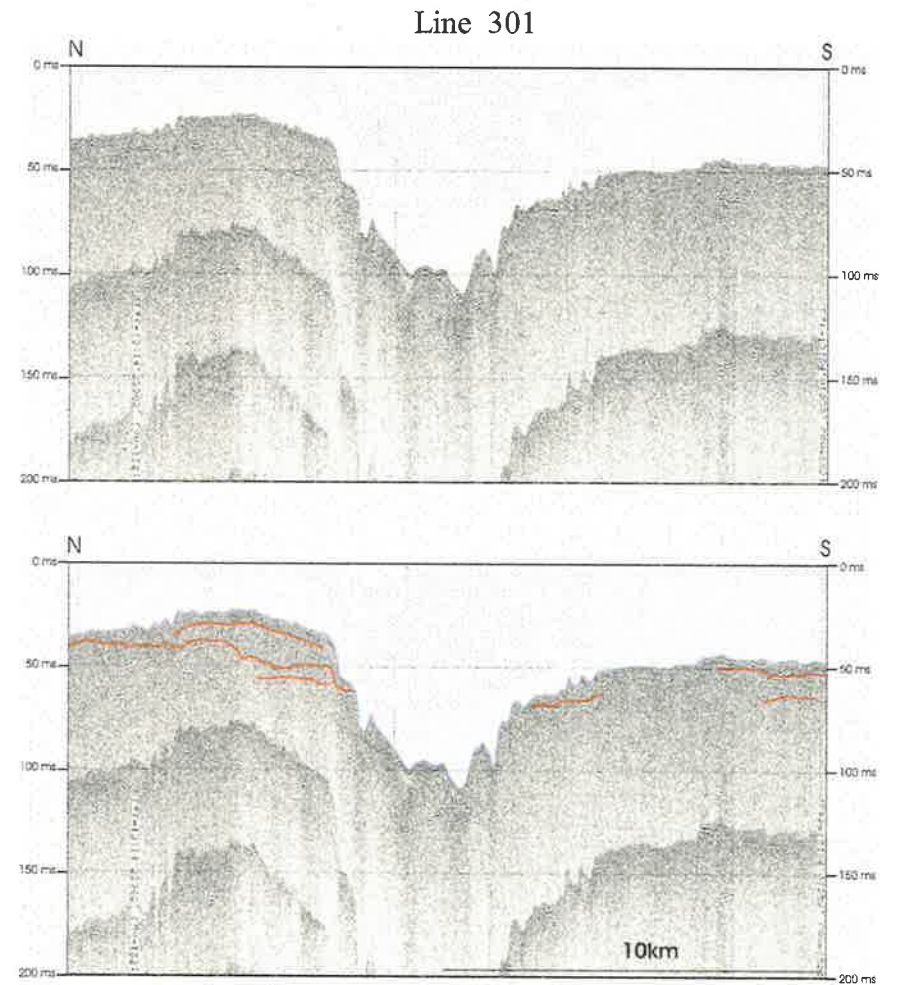


Figure 5.12 Bathymetric profile (top) and the interpreted sub bottom profile of line 301 (bottom)

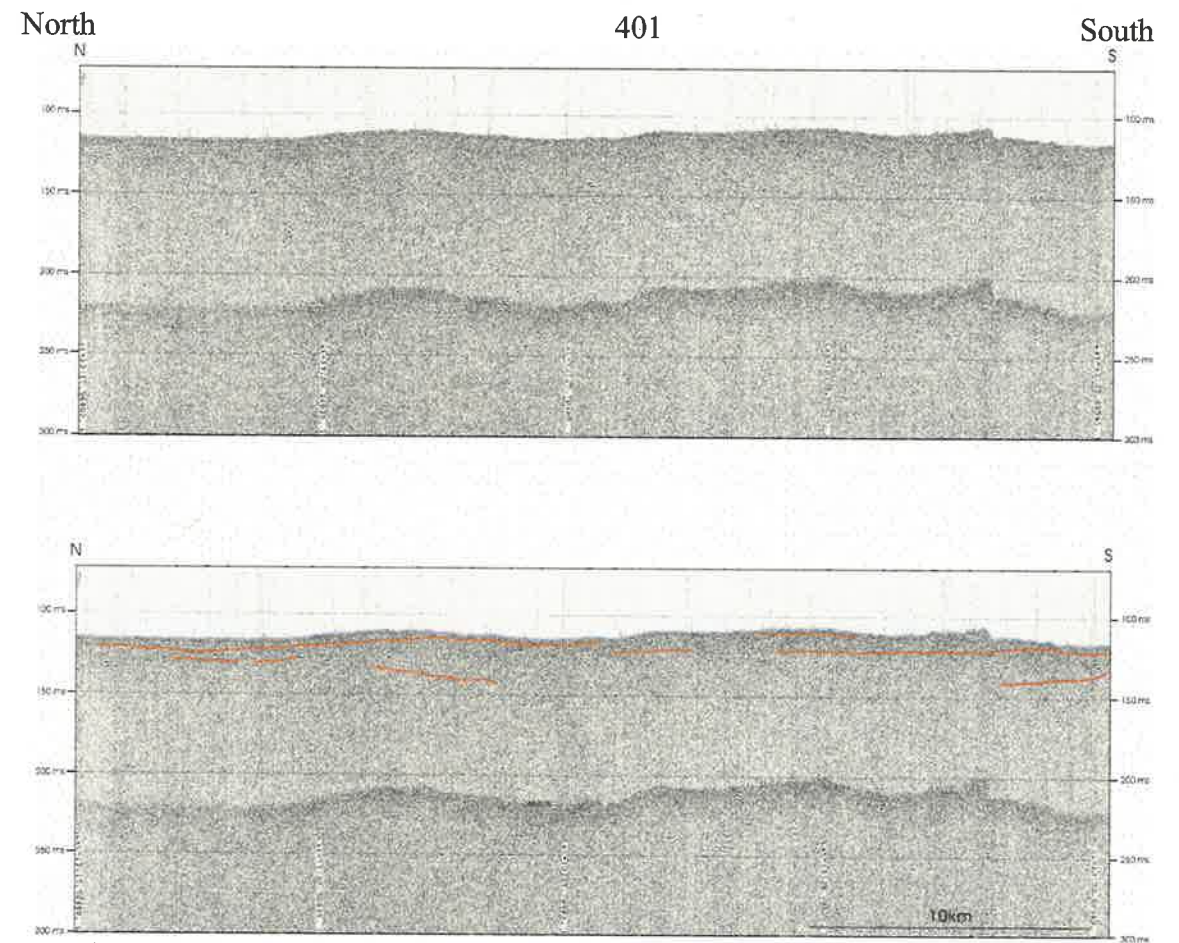


Figure 5.13 Bathymetric profile (top) and the interpreted sub bottom profile of line 401 (bottom)

5.5 General observations and Interpretation of the Penguin Deeps Seismic sections

The 231.21 km of seismic acquired for this study yields an uninterrupted history of recent depositional sequences for the NW Shelf. As the boundary size for the main depo-centre is approximately 75 X 100 km and the average thickness of the deposition on top of the 'karstic' red line is ~40m, then as a first pass, <300 km³ is deposited in this off shore shelf slope sediment trap over time.

5.5.1 Seismic Line 101

Line 101 68.74 km long. It leads out into the deeper water of the Browse Sea Valley and shows five major depositional events that were deposited in rising, falling and stable sea levels. It clearly shows several depositional events on top of channelised base. This base appears to result from multiple depositional and erosional events that have been subsequently in-filled with planar sediment packets. These planar depositional features are indicative of abundant sediment supply.

These planar features are overlain by multiple depositional events, One identified by the magenta line, its shape indicates a stable SL with multiple prograding features once again demonstrating the abundant sediment supply.

Towards the top of the sediment packets, but prior to the Holocene sediment cap, a channel feature is observed indicating that both deposition and erosion were effective sediment controls throughout the recent geological history.

The sequential sedimentological history of the Penguin Deeps Channel and fan interpreted from the seismic record 101

1. The base as seen on the seismic image of the Penguin Deeps line 101 are inferred to represent multiple layers of marine carbonates (?). (SL rising)
2. Red line. This surface appears to result from multiple events of karstification or extensive channelling. Thought to have occurred when relative SL was low. (SL falling)
3. Blue Line. The planar deposition of sediments over the karstified (?) surface would have occurred during a relative higher SL (SL rising).
4. Light Green line. Planar deposition of the next layer represents deposition during a rising SL indicating abundant sediment supply (SL rising). Magenta line. Deposition of prograding sediment packets when SL was stable (SL stationary). Abundant sediment supply.
5. Orange Line. Deposition on a rising SL (SL rising).
6. Yellow Line. Deposition on a rising SL (SL rising). This is a different episode to the previous orange layer.
7. Red Line. Erosion and fluvial channelling of the shelf. Lower SL.
8. Light Blue Line. Holocene deposition of sediments throughout the study area based on sediment cores, at least to a depth of ~5m. This layer caps all previous layers and is made up of reworked shelf sediments, terrestrial material and fresh organic carbonates (eg. benthic foraminifera, bryozoa, corals) transported in from the Bonaparte Basin and *insitu* derived material.

5.5.2 Line 201

Line 201 shows a fall of over 75ms from the shelf proper and shows four main depositional events. The seismic line runs down through the highly rugose Penguin Deep, over the topographically positive feature, interpreted to be a barrier bar which also delineates the shelf break. From here the line runs across the depositional basin associated with the Penguin Fan ending near one of the linear positive features running parallel to the Browse-Bonaparte transition zone. Prograding sediments packets are clearly identified and smaller depositional events within these indicate a strong sediment supply being introduced during all sea levels.

Line 201 is 105.5 km in length is the longest seismic line of Survey 225. The bathymetry of this, when viewed from the east, exhibits a planar shelf dropping onto some highly rugose topography associated with the Penguin Deep channel. The channel bathymetry flows out onto a gentle rise to the 'barrier bar' that physically delineates the shelf break. The sudden drop leads onto an extensive undulating sea floor profile punctuated by the intersection of the linear topographically positive feature that appears to have its genesis associated with an underlying feature.

The seismic profile clearly shows episodic deposition and erosion events. These events are dependent on the height of sea level and the availability of sediment.

Deposition record from Seismic Line 201

1. The base as seen on the seismic image of the Penguin Deep line 201, are inferred to represent marine carbonates (?) laid down at depth, under water. (SL rising).

2. Red Line. These multiple surfaces appear to be karstified or extensively channelled. Considered to have occurred when relative SL was low.
3. Blue Line. This appears to be a pull up, related to the topographically positive feature with a faster signal. SL perhaps during a relative higher SL.
4. Light Green line. Planar deposition of the next layer represents deposition during a rising SL.
5. Orange line. Multiple deposition events on a rising SL.
6. Yellow line. Deposition on a rising SL. This is a different episode to the previous orange layer.
7. Light Blue Line. Holocene deposition of sediments throughout the study area at least to a depth of ~5m. This layer caps all previous layers and is made up of reworked shelf sediments, terrestrial material and fresh organic carbonates (eg. benthic foraminifera, bryozoa, corals) transported in from the Bonaparte Basin and *insitu* derived material.

5.5.3 Line 301

Line 301 displays the profile of the Penguin Deeps channel revealing it to be steep sided and the plan views show it to be linear. This is indicative of a fast flowing river and therefore an effective sediment conduit. While none of the secondary channels have any bilateral indicators that correlate, the morphology indicates that throughout its developmental history, the Penguin Deeps had varying flow regimes. The water flow was an effective eroding agent, cutting paths on both sides of the larger channel.

Line 301 is 20.28 km in length. The seismic section runs perpendicular to the Penguin Deeps channel, and illustrates significant topographical variation of > 70m. The North side of the channel is higher than the south and both sides have steep profiles. None of the secondary channels within the large primary Penguin Deeps channel share the same depth or any other indicators indicative of bilateral correlation. This indicates that throughout its developmental history the Penguin Deeps had varying flow regime across its width. With no one path being dominant and the water flow was effective in eroding agent cutting paths on both sides of the larger channel. There appears to be no apparent deposited bed load signal in the seismic.

Both sides of the channel appear to have capping rock, yet the seismic signal is incomplete and ambiguous, and therefore inconclusive in providing the depositional sequences.

Deposition record for line 301

1. Yellow Line. Two multiples of the bathymetric signals are seen on the image.
2. Red line. Multiple surfaces appear to be karstified or extensively channelled. Considered to have occurred when relative SL was low. Their quasi planar top surfaces indicate an erosional SL relationship.
3. Light Blue Line. Holocene deposition of sediments throughout the study area at least to a depth of ~5m. This layer caps all previous layers and is made up of reworked shelf sediments, terrestrial material and fresh organic carbonates (eg. benthic foraminifera, bryozoa, corals) transported in from the Bonaparte Basin and *insitu* derived material

5.5.4 Line 401.

The Penguin Fan barrier bar shown in line 401 reveals a subdued morphology with some reworking of the surficial sediments by fluvial processes. The absence of any meaningful reflectors indicates that there are no distinct depositional events and that the reworking of the sediments has produced a homogenous sand barrier. Line 401 is 36.69 km in length. The seismic section runs south across the barrier bar. This bar is spatially associated with the shelf break, and is perpendicular to the flow direction of the Penguin Deep. It highlights the subdued topographically associated with this depositional feature.

The depositional record gleaned from this section is at best limited. What is apparent is the lack of any significant vertical variation, the subdued features have one exception, a small scarp on the southern most section of the seismic image in the most recent sediments.

This would have formed at times of a lower SL in response to a river path for the water flowing out of the Penguin Deep. Supporting this scenario is that it has a levee profile.

Deposition record from Seismic Line 401

1. Yellow Line. Seismic multiple.
2. Red Line. These multiple surfaces may be karstified or erosion surfaces. Considered to have occurred when relative SL was low and sediments were exposed.
3. Light Blue Line. Holocene deposition of sediments throughout the study area at least to a depth of ~5m. This layer caps all previous layers and is made up of reworked shelf sediments, terrestrial material and fresh organic carbonates (eg.

benthic foraminifera, bryozoa, corals) transported in from the Bonaparte Basin and *insitu* derived material.

5.5.5 Seismic Summary

All of the seismic information indicates that this is an area of high deposition over time. Strong sediment supply has made several significant sediment packets each with smaller events recorded in the profile. Erosion has also taken place with the channelling of the base and the shelf sediments and with the evolution of the Penguin Deeps and Browse Sea Valley.

There are two main advantages of obtaining the seismic of the Penguin Deeps region. At a first pass the shape and extent of the sediment packets indicate deposition on all rising falling or stable sea levels. Future work could tie this in with the SL over time.

But perhaps the most important addition is that by identifying the thickness of the sediment accumulation sequences, the seismic images give an indication as to the amount of sediment deposited in this restricted depositional region (Table 5.1).

If the layer of Holocene sediments is averaged out at 5m across the Browse Sea Valley (~75 X 100km). Then 35km³ of sediments has been introduced to the fan over the past 11 ka. The potential terrestrial contribution is 42 km³ (Chapter 2.6) and an unknown quantity of this will be dissolved, and or, transported off and deposited in deeper water environments or entrained in ocean currents. To give a variance of area both 7 x 10⁶ and 6.05 x 10⁶ have been presented in Table 5.1.

Sediment meters deep	Penguin Deeps Fan / Browse Sea Valley area 6 050 000 km ²	Penguin Deeps Fan / Browse Sea Valley area 7 000 000 km ²
3	18.15 Km ³	21 Km ³
4	24.2 Km ³	28 Km ³
5	30.25 Km ³	35 Km ³
6	36.3 Km ³	42 Km ³

Table 5.1 Deposition in the Browse Sea Valley

5.6 The Kimberley Shelf-slope transect

Observations in this study show that although similar to the Bonaparte Shelf, the narrower Kimberley Shelf, southwest of the Penguin Deeps (Figure 1.1), comprises a smaller area, and exhibits more clearly the relations between similar physiographic features to those found on the Bonaparte Shelf. The following description of the nature of a bathymetric cross-section across the Kimberley Shelf and adjacent slope, uses the available seismic (Figure 5.10 – 5.13) and sedimentological (Chapter 3 and 4) information to arrive at a best interpretation of the physiography of the shelf and adjacent upper slope. Though developed specifically for the Kimberley Shelf transect, the arguments and interpretations presented can also be applied, with only minor modification to the Bonaparte Shelf.

5.7 The Holocene inner shelf sediment prism and subjacent inner shelf platforms

5.7.1 The near-shore area

The western coastline of the Kimberley Block, between Cape Londonderry and King Sound, is deeply embayed and often cliffed. The strong tidal currents which characterize the region (Lees 1992) have created erosive sea-floor topography around projecting headlands and within channels which reach down to at least 30

m water depth off the mouth of major inlets such as Admiralty Gulf and Vansittart Bay on either side of Cape Bougainville (Figure 1.1). The ria and adjacent coastal embayments, away from areas of concentrated tidal flow, contain a thick inshore sediment prism of muddy Holocene sediment up to several tens of metres thick. Within, and extending offshore from, Montague Sound, one sediment body within this shore-connected inshore sediment prism extends alongshore for 60 km, is 40 km wide, and has its northeastward-running seaward edge delimited by the 10 m isobath, just outside the Maret Islands (Figure 1.1). The inshore sediment prism downlaps onto, and in places completely covers, what appear to be the three shallowest shelf platforms, which have seaward edges at depths of ~30 m, ~45 m and ~60 m, respectively.

5.7.2 The 75 m-deep, mid-shelf terrace

A wide area of the Kimberley middle shelf, 40-50 km-wide and stretching for more than 200 km along-shelf, and a significant area on the Greater Londonderry Rise, is underlain by this terrace. With an inner edge at ~65 m, the 75 m-terrace has an extremely low seaward slope of 1:10 000. The terrace surface is irregular, with up to 5 m of relief, and isolated banks, which rise to depths of 60 m near its outer edge and along the line of the Heywood Shoals spur. Seismic line 201 (Figure 5.11) crosses only the outer few km of the 75 m-terrace, and shows that it has a hard, reflective surface, consistent with cementation and or encrustation.

5.7.3 The 95 m-deep, outer mid-shelf terrace

The 95 m-terrace is well developed on both sides of the Heywood Shoals spur and also covers a wide area of the eastern Londonderry Rise. Seismic line 101 (Figure

5.10) shows that in the head of the Browse Sea-valley, (part of which is the Penguin Fan) the terrace is 22 km-wide and has inner and outer parts of different character. The inner half of the terrace is conspicuously irregular. This zone abuts the 15-m high riser up to the 75 m-terrace, which encompasses a small sediment apron with rounded topography and a shallow moat. All these features are suggestive of current erosion at some time after the terrace was last flooded, though not necessarily at the present time and depth.

The outer part of the 95 m-terrace exhibits a smooth, slightly undulating seabed surface which rises in a 40 km wide, 10 m-high sediment mound just inboard of the sharp terrace edge. On bathymetric maps, and profile 401 (Figure 5.13) which also crosses this feature, the sediment mound is seen to be almost linear in long dimension, and trends north south at the terminus of the Penguin Deep. The biogenic carbonate sediments here are predominantly intermediate and relict sands and gravels. Aggradational bars of this nature are not known to be forming on the outer part of Kimberley or Bonaparte mid-shelves today, implying that this feature is probably relict.

The inner part of the 95 m-terrace has a similarly reflective nature to its 75 m-terrace counterpart. The presence of loose sediment at the seabed however, has permitted penetration of the seismic pulse beneath the outer terrace, revealing the presence of a horizontal reflector (?older terrace surface) about 15 m below the seabed. A zone of small channels occurs seaward of, and at lower levels than, this reflector.

5.7.3.1 Model for the Penguin Deeps barrier bar formation

The Penguin Deeps barrier bar feature found principally as an interpreted LGM entrenched fluvial feature, when a river flowing through the Penguin Deeps Channel flowed directly out into the Indian Ocean. It may represent a shallow marine mouth bar deposited at the outer edge of the 95-m terrace, just offshore from the Penguin Deeps river mouth, early in the post-glacial transgression when sea-level stood at ~ 85 m (Figure 2. 15). Comparison with a global sea-level curve indicates, for such a shoreline depth, an age of ~ 13.5 ka (Siddall et al., 2003).

The speculation that the modern submarine geomorphological expression of the Penguin Deeps Fan has resulted from a wave modification of a fluvial canyon as it opens out onto a wider valley (termed as the Browse Sea Valley) is presented in Figure 5.14. Marine waters now flow through the Penguin Deeps into the Indian Ocean, with topographical highs on either side assisting in directing the flow. The barrier bar at the 'front' of the submerged 'Penguin Delta' is interpreted to be a drowned front of a wave-dominated delta.

Alternatively, and less consistent with its plan-view morphology, the feature could represent a coastal sand dune complex or blowout deposited just inboard from a slightly deeper and slightly older shoreline at ~ 100 -105 m depth.

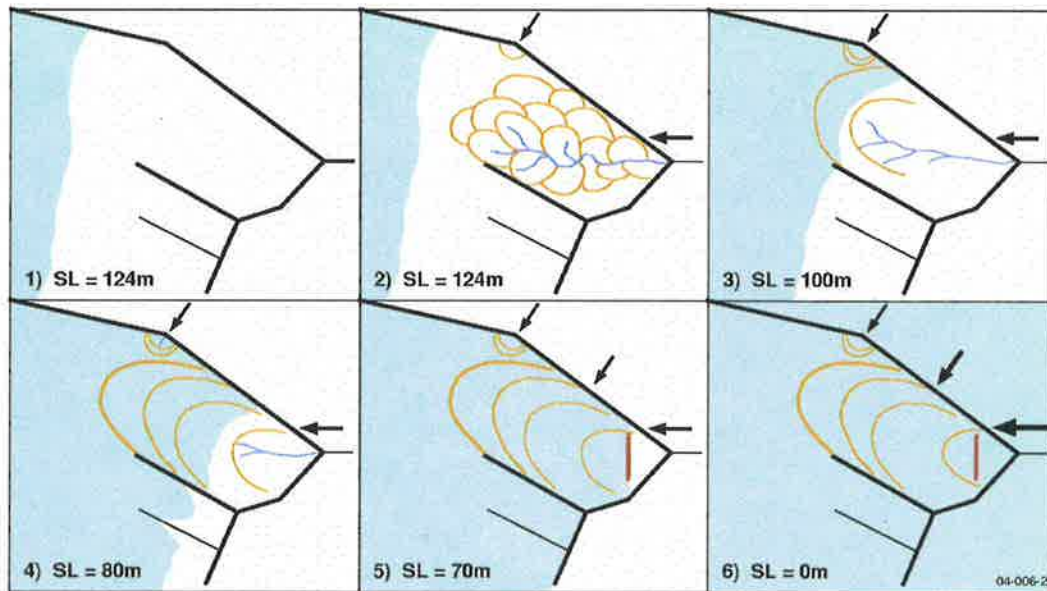


Figure 5.14 A development model of the Penguin Deeps barrier bar from this study. Arrows indicate the direction of sediment inputs over time

The barrier bar and subaqueous fan lie below the storm wave base, yet it would receive sediment due to the storm induced re-suspension and transport from shallower area on the Bonaparte Basin, and from favourable hydrological and gravity driven currents from the Penguin Deeps.

5.7.4 The 112 m-deep outer shelf terrace

The 112 m-terrace has a complex morphology and composite nature (Figure 5.10). On the seismic transect along the south slopes of the nearby Browse Sea-valley, the terrace possesses a hummocky but otherwise nearly horizontal top and is separated from the seaward edge of the 95 m-terrace by a marked 10-15 m high riser. Similarly to the riser at the back of the 95 m-terrace, the riser which separates the 112 m- and 95 m-terraces is accompanied by a well-developed 30 km wide, seaward-tapering sediment apron, with a narrow 5 m-deep moat hard against the riser wall. These features indicate long-shelf current activity here at some time after the 95 m-terrace was flooded, with the sharpness of the

bathymetric features suggesting that the current activity may continue today.

Here and elsewhere nearby the terrace is typically 25 km-wide, and lies at depths of 105 to 112 m. The riser and terrace together are equivalent to the widely remarked, 50-60 fathom (~90-110 m) deep, last glacial shoreline of earlier writers Fairbridge (1953), van Andel and Veevers (1967). Seismic penetration beneath the 115 m-terrace is good, with delineation of reflectors up to at least 75 m deep beneath the seabed.

5.8 Possible relict shorefaces

Line 201 exhibits two apparently distinct shoreline features (A and B) at similar, but probably not identical, depths.

5.8.1 Relict shoreface A.

The seawards feature (A3) comprises a small, interpreted drowned reef complex which peaks at 108 m depth (Figure 5.10). On its downslope side this reef displays a peripheral, 10 km wide sediment apron (A4) and accompanying minor moat, whereas the upslope side of the reef delimits the toe of a sediment prism (A2) which onlaps a hummock (A1) of probably sandy sediment that rises about 3 m above the terrace surface in this vicinity. The appearance is that of a shoreface prism onlapping a beach and foredunes, accompanied by a nearby inshore reef and, landward of the beach, by a slightly undulating coastal plain, perhaps with an estuarine channel. The landward pinchout of the sediment prism and the top of the reef pinnacles occur at a common depth of 108 m, which, if this interpretation is correct, would represent the contemporary sea-level. Other than the reef, below which there is no seismic penetration, the sediments associated with this

interpreted shoreface comprise a thin veneer which reaches a maximum thickness of ~7 m within the sedimentary prism.

In the absence of detailed samples and more seismic information, this shoreface interpretation cannot be proven. An alternative explanation, for example, would be that the described features all had their genesis as terrace-edge features (i.e. as an edge sediment bank, sediment apron and nearby patch reef) in shallow shelf waters a little after the marine flooding of the terrace by a rising sea-level.

Alternatively again, the reef and terrace edge might represent deep, outer shelf relict features, with the sediment prism comprising a younger middle or inner shelf sediment accumulation ponded between the terrace edge and the reef.

5.8.2 Relict shoreface B.

Sediments associated with the 108 m-shoreface overlie the deposits of a major, progradational sediment prism (B1). The tapering-seaward toe of this prism (B2) is well displayed on downslope profile 101, and profile 201 displays also a landward taper. The prism is up to 60 ms (45 m) thick), displays faint but distinct, slightly sigmoidal, clinoform bedding towards the northeast (downslope, and oceanwards), and has a seaward slope which commences at a seafloor depth of ~112 m. Topsets within the prism are in part eroded at the base of the overlying Shoreface A sediment packet, but thin topsets (B3) can be traced back to a point of possible coastal onlap near the seafloor depression on the middle of the 112 m-terrace on Line 201. Landward of this onlap, sediments at the equivalent stratigraphic level to the progradational prism display strong nested channel nature (B4), consistent with estuarine or fluvial deposition on an adjacent coastal

plain. The seismic penetration through the progradational prism, and a lack of strong internal reflectors, is strong evidence that it has a composition of uniform mud, and portions of prism B downlap onto either a (buried) terrace at ~ 140 m-depth or onto an older and underlying sediment prism (see prism C, below).

The main clinoform body of prism B is overlain by a sediment drape up to a few metres thick, which appears as a downslope continuation of the small upslope sediment prism A2. That core GC 10 penetrates into this drape, and contains early Holocene radiocarbon dates (Table 5.2) indicates that the core did not penetrate to the body of prism B, and that the drape is stratigraphically distinct from the probably relict sediments below.

Core depth	AMS Date	error	Accumulation rate
0.0m	5066.000	40.000	
0.9m	9155.000	50.000	22.01
1.9m	11432.000	55.000	43.91
2.9m	11880.000	55.000	223.21

Table 5.2 The radiocarbon dates of sediment core #10 from the Browse Sea Valley and their accumulation rate.

Geometrically, progradational prism B is closely similar to the modern terrigenous ISPs which occur along the inner Kimberley Shelf. It is therefore interpret it as a drowned, relict sedimentary prism which was deposited adjacent to a shoreline only slightly deeper than shoreline A, at about 112 m depth. The fine-grained composition of prism B might be either dominantly terrigenous, dominantly micritic, or a mixture of both, depending upon the nature of the nearby shoreline source.

Alternatively, and with the radiocarbon data in mind, the prism may have been deposited as an offshore sediment body about mid-way through the post-glacial

transgression, perhaps when the mouth of the Penguin Deeps channel was flooded for the first time with the release of a pulse of carbonate sediment to the shelf. Sediment pulses of this type have recently been shown to characterise the post-MIS 2 transgression on the Great Barrier Reef shelf (Dunbar et al. 2000). In applying such an interpretation to prism B, however, it is difficult to envisage a plausible mechanism that could have caused the prism to have such a flat top.

5.8.3 The 150 m sediment prism: relict shoreface C?

The 112 m-depth sediment prism prograded seawards across the top of a morphologically similar prism located in deeper water near the outer shelf-upper slope junction. This older prism, C, also exhibits double tapering, clinoform and seismically transparent characteristics, and has a ~4 m-thick topset-foreset drape. Prism C achieves a maximum thickness of 45 msec (34 m), has a palaeo-seafloor clinoform breakpoint (below the drape) at ~155 m-depth, and an inferred upslope onlap at ~150 m-depth. The inboard portions of Prism C onlap onto a conspicuous (buried) 165 m-terrace, whereas the toe of the prism downlaps onto a probably relict sediment pocket at the seaward end of a long slope of degraded intermediate risers and terraces between the 165 m- and ~200 m-terrace.

5.9 Origins of Continental Shelf Terraces

5.9.1 The origins of a single, regional continental shelf surface

The origins of a single, regional continental shelf surface (or “continental terrace”) and the origins of multiple submergent terraces such as exist on the Sahul Shelf, have not always been clearly distinguished. Lewis (1974) for instance, gives an excellent summary of historic views regarding the erosional, depositional or tectonic origins of the continental shelf, worldwide, and Teichert

and Fairbridge (1948) provide an insightful discussion of possible interpretations for the Sahul Shelf terraces. Yet both discussions centre strongly around the same possible factors of erosion (wave planation), deposition (sediment prism progradation), and tectonics / eustasy; processes which both control the levels at which erosion and deposition operate, and also create and destroy accommodation space.

In a classic study of the origins of Australian continental shelves, Carrigy, and Fairbridge (1954, pp. 87, 90) commented that “even a preliminary consideration shows clearly that there is no one causal phenomenon that accounts for all sectors of these continental shelves all shelves are complex and of compound (tectonics-sedimentation-erosion-eustasy) origin”. Whilst this statement is obviously true, in a general sense it is also true, as has been agreed by most researchers on the area, that the Sahul Shelf platform has a “single” continental shelf with an edge at around 90-110 m. It does not, however, follow that the shelf as so-defined has a single mode of origin. As outlined earlier, the regional Sahul “shelf” comprises a pastiche of areas with terraces at consistent levels, and, though there may be a common principle of general origin for all the terraces, each discrete terrace must have its own singular history. This principle of interpretation is explored in more detail below.

5.9.2 Continental margin terraces: the interaction between eustasy and tectonics

The recognition that fundamental physiographic differences exist between emergent and submergent coasts (and adjacent shelves) goes back to such early classics of geomorphological writing as Davis (1898) and Johnson (1919).

Despite this understanding, a fundamental ambiguity underlay interpretations of continental shelf and coastal marine terraces even as late as the mid-20th century (e.g. Cotton 1955), because of the lack of knowledge then regarding the frequency and magnitude of Quaternary glacio-eustatic sea-level fluctuations and the numeric rates at which coastal tectonic processes operate. Great improvements in understanding of these two issues occurred in the 1960s and 1970s, which led to several classic studies of the *ascending flights* of coastal terraces that result from interaction between repeated glacio-eustatic sea-level change and an *uplifting* coastal hinterland (e.g. Chappell 1974a; Chappell 1974b; and Pillans, 1983).

The parallel creation on a *sinking* margin of a *descending flight* of submarine terraces has been less well studied and is less well understood. Perhaps because the main geomorphic result lies underwater, but also importantly because submarine terraces were most often interpreted as marking the position of lowstand shorelines (e.g. Pratt and Dill, 1974). However, Lewis's 1973 study of the influence of glacio-eustasy on the development of sedimentary prisms on the eastern New Zealand shelf provides much insight into the general principles involved. In this context, the Sahul Platform is a globally historic area where earlier investigators noted that the geomorphology of the shoreline indicates a submergent coast (Cotton 1956), and therefore invoked a subsidence origin for the prominent submarine terraces which occur on the adjacent shelf and upper slope (Teichert and Fairbridge 1948; van Andel and Veevers 1967).

5.10 Evidence for recent glacio-eustasy

Worldwide, continental shelves display bathymetric or sedimentary features which reflect late Quaternary glacio-eustasy. This has led to a voluminous literature. Features which have been described include submerged river valleys (e.g. Swift et al. 1980), wave-cut terraces (e.g. Wagle et al. 1994), submerged bodies of littoral sand (e.g. Ferland et al. 1995) or pro-delta mud (e.g. Tesson et al. 1990), and submerged corallgal reefs (e.g. McIntyre 1972). These features are inferred to have developed when sea-level was at the MIS-2 lowstand, or during pauses in the post-glacial transgression, and to have become drowned by the occurrence of further sea-level rise to the full Holocene interglacial level. Far removed from areas of glacio-isostatic rebound, such shoreline features may be preserved at depths close to their original depth of origin and can sometimes be traced laterally for hundreds of kilometres (e.g. Emery and Garrison 1967). Many authors have used drowned features like these in attempts to reconstruct local sea-level curves, by assuming that their preservation indicates a relatively recent origin (i.e. that they are most likely post-glacial in age) and that they become successively younger with decreasing depth (Dillon, and Oldale 1978; Carter and Johnson, 1986). Radiometric and other dating techniques have confirmed that some features were indeed developed during or after MIS-2, but others have proved to represent older glacial or post-glacial events. Therefore, and as cautioned by Harris and Davies (1989) for the GBR shelf, great caution should be exercised in interpreting undated features from the continental shelf solely in terms of the most recent glacio-eustatic cycle.

5.11 The terraces of the Sahul Shelf

5.11.1 The Sahul and Kimberley Shelf terraces

The occurrence of terraces at systematic depths on the Australian continental shelf and upper slope was first reported by Teichert, and Fairbridge (1948), and shortly after those on the Sahul Shelf were described in some detail by Carrigy, and Fairbridge (1954); Fairbridge (1953) and Carrigy and Fairbridge (1953). More detailed interpretations of the physiography of the Sahul Shelf, based mainly on bathymetric profiles and seabed sediment grab samples, were made by van Andel and Veevers (1967).

The Sahul and Kimberley shelves are characterised by a low (1:1000, Kimberley shelf) to very low (1:4200, larger Bonaparte Shelf) seawards slope towards a shallow shelf-break at ~90-110 m-depth. Superimposed on this shelf and on the adjacent upper slope down to depths of at least 200 m are a series of terraces or platforms which often display irregular, hummocky tops. The platforms generally have a gentle seaward slope of similar magnitude to that of the surrounding shelf surface, and are separated by narrow ~15-25 m high scarps or slopes. Isolated reefs or shoals may rise to or towards sea-level from terraces of all depths out to and even beyond the shelf-edge. The Bonaparte Depression, Malita Shelf Valley and related smaller shelf-channel features occur further northeast, on the central Sahul Shelf. All earlier writers have agreed, together with Jongsma (1970b) that “the morphology is that of a submerged subaerially eroded landscape, with a fluvial pattern of channels and drowned reefs near the edge of the shelf. Near the Australian coast the old subaerial topography has been covered by fine grained marine sediments”. But whereas some writers believe that this land surface was

shaped at the last glacial maximum (e.g. Carrigy and Fairbridge (1954) ; Fairbridge (1953) and Carrigy and Fairbridge (1953) Lavering (1993)) saw it as resulting mostly from a late Pleistocene phase of tectonic sinking of the whole Sahul platform, albeit with an overlaid eustatic influence.

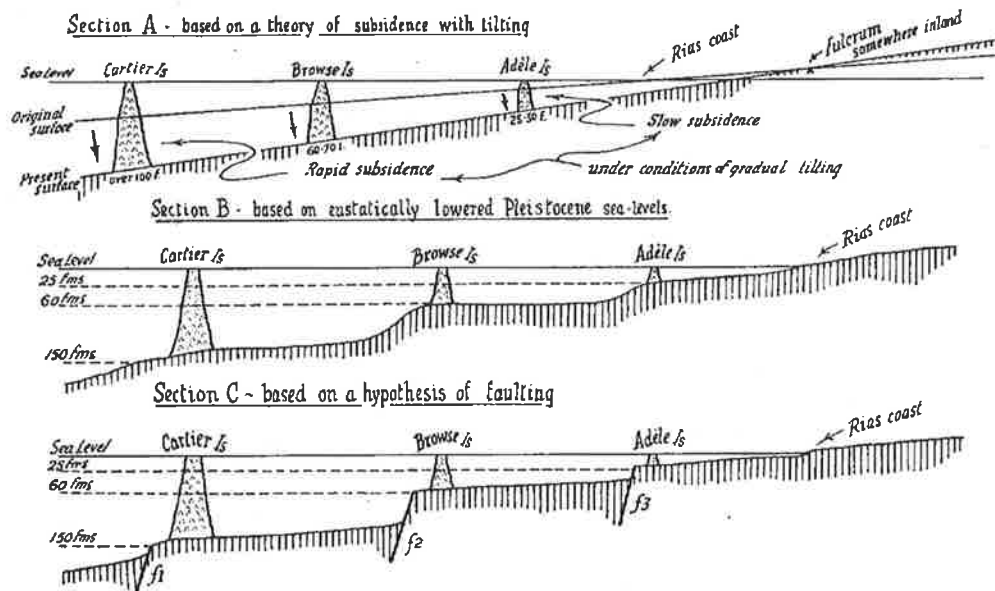


Figure 5.15 Three Sahul shelf reef and terrace development models (from Carrigy and Fairbridge 1953)

Teichert and Fairbridge (1948) and Carrigy and Fairbridge (1953) presented three alternative explanations for the Sahul shelf reef and terrace development, with a classic diagram of tilting, eustasy or downfaulting (Figure 5.15). None of these interpretations were seen as adequate to explain the shelf morphology on its own, but “the topography suggests a former subaerial exposure, shown by submerged land forms of arid type with clear terraces (and) shallow canyons”. Concluding that "eustasy is assumed to occur in any case, (but that) it cannot explain the situation completely", these authors preferred as an interim working hypothesis a combination of eustasy, tilting and downfaulting. In sum, they interpreted the

Sahul Shelf platform and its superposed terraces as originating as now-drowned coastal plain(s) which were constructed at times of eustatic sea-level lowstand. Following similar logic, van Andel and Veevers (1967, p. 697) commented that "the system of sea-level changes needed to explain all surfaces is improbably complex", and therefore followed Fairbridge (1953) in assuming that this relief equated with that on the nearby coastal plain and was caused by one-off submergence off the coastal plain by about ~100 m sometime in the Late Pleistocene.

Thus, whilst acknowledging some role for eustasy, all previous authors have assumed a primary role for subsidence in shaping the morphology of the Sahul Shelf, and especially in creating the conditions suitable for coral reef pedestal growth along the shelf edge. Such subsidence, the zero isobase for which must be located inboard of the modern shoreline (Lewis 1974), also explains the existence of drowned ancient-reef equivalents at depths down to ~240 m (Dill 1969). Alternatively, these features, and analogous deep terraces in southern Australia, were attributed by Jongsma (1970a) and Pratt and Dill (1974) as resulting from older (and larger magnitude) mid-Pleistocene eustasy.

5.11.2 A model for the origin of flights of submergent terraces on a subsiding shelf

The terraced nature of the Kimberley (and, more widely, the Sahul) Shelf is ascribed here to the interaction between late Quaternary glacio-eustatic sea-level change and a shoreline-shelf system which has been subsiding at a rate of ~15 cm/ky for probably at least the last 2.5 m.y. The process is conveniently considered in terms of a small number of basic steps, described below. Cyclic repetition of these steps results in the creation of a flight of submergent terraces across the continental shelf and upper slope.

5.11.3 Formation of a primary highstand platform

A primary terrace surface is formed on both sides of a highstand shoreline, such as today's. The surface is composite, and comprises a *coastal plain* (aggradational, possibly with superposed chenier and incised tidal or fluvial channels), a *shoreface* (including areas of possible marine-planed rock platform and sea-level controlled fringing reef) and a progradational, flat-topped, muddy, *bay-fill inshore sediment prism*. Typically, the inner edge of the coastal plain might lie at up to ~ +10 m above sea level and the seaward edge of the prograding inshore sediment prism at ~ -10 m below sea level, with the widths of each reaching up to 10 km or more. Thus, other than across the very narrow shoreface itself, which will exhibit a slightly greater slope, a primary highstand platform is characterised by low seaward slopes of 1:1000 or less.

Obviously at different points along the coast, (or for platforms formed in different eustatic highstands), the component parts of a platform will differ in their areal proportions, and sometimes particular parts may be absent altogether.

Recognition of the composite nature of a primary highstand platform - one consequence of which is that the seaward and landward edges of the platform can differ in height by up to ~20 m, and that before adding the effects of any subsequent deposition or erosion - may go a long way towards explaining why earlier researchers have had such trouble matching the precise heights of drowned shelf terraces over significant distances (cf. Harris and Davies, 1989).

5.11.4 Formation of succeeding regressive or lowstand platforms

In principle, similar primary terraces could be formed on the shelf or upper slope during pauses in the regression towards, or at, the succeeding eustatic lowstand. A shelf-slope system which has been subsiding for a considerable period, however, such as the Kimberley Shelf, the seafloor down to lowstand depths (100-120 m) will already carry relict terraces which formed during earlier highstands and then subsided to shelf and slope depths.

Accordingly, features associated with regressive or lowstand shoreline positions will in general be superposed on some part of a pre-existing submergent highstand terrace or terraces, which will thereupon become palimpsest in nature. All of the features that are normally associated with a new highstand terrace may during regression or lowstand be superimposed on top of areas of relict terrace, including

particularly the deposition of detrital ISPs, the growth of areas of reef (and surrounding bioclastic reef sediment prisms; RSP) on appropriate precursor surfaces, and the bioerosion or wave-planing of areas of hard substrate

5.11.5 Subaerial modification of pre-existing terraces

In addition, when significant regression has occurred towards the next glacial lowstand, wide areas of the previous highstand platform - and, increasingly during regression, successively older relict highstand platforms preserved on the inner and middle shelf - will be left exposed on the new, widening coastal plain. Here, these platforms will become subject to alteration by subaerial and fluvial erosion, including pedogenesis and groundwater flow. The type of alteration, or destruction, will clearly depend upon the differing physical characteristics of the materials that comprise a particular terrace, which will range from cohesive soft mud of the inshore sediment prism platform, easily remobilised sand and gravel from the shoreface and coastal plain, to harder, increasingly resistant- to-erosion substrates such as coralgall reef flat or marine-planed bedrock platform. These differing substrates will react in different ways when the primary platform is exposed, and the platforms will be variously veneered, eroded, channeled, cemented and encrusted depending upon the particular compositions of their component parts.

5.11.6 Formation of subsequent (second) primary highstand terrace

During the Quaternary, an interglacial-glacial-interglacial cycle became complete when the sea-level rose from its lowstand position to the next interglacial

highstand. At this time, a subsequent (second) primary highstand terrace is formed.

With the lapse of 100 ky between late Quaternary highstands, when the shoreline returns to its former interglacial level the primary terrace formed during the previous highstand will have subsided to inner shelf depths, the precise depth depending upon the local rate of subsidence. On the Kimberley Shelf transect (Figure 5.10), the seaward edge of several of the most recent terraces preserved across the shelf are separated vertically by ~15 m (Figure 5.11), which suggests that the shelf has been subsiding at a fairly steady rate of ~15 cm/ky back to at least 0.5 Ma.

5.11.7 Submarine modification of pre-existing terraces

As post-glacial shoreline transgression occurs towards the next interglacial highstand, older, originally primary highstand but now poly-palimpsest, highstand-regression-lowstand-transgression-modified terraces will become drowned at various depths across the continental shelf. At the succeeding full highstand, the most recent primary terrace (the one that formed in the highstand of the previous eustatic cycle), now itself palimpsest, will be preserved on the inner shelf at ~15-25 m depth, i.e. at its original palaeodepth of ~0-10 m plus the ~15 m of subsidence which has occurred in the 100 ky since its formation. After being subjected to any erosion which may be associated with the transgressive shoreface, this terrace (and sometimes also parts of the penultimate, next older, next seaward terrace) will become buried beneath the new highstand inshore sediment prism. Parts of the shelf outside of the zone of inshore sediment prism

influence, which comprise older submerged highstand terraces, thereby come to lie in an offshore zone of starved or condensed sedimentation. During highstands, therefore, the surfaces of these older terraces become bored, burrowed, encrusted, overgrown with patch reefs or covered with a veneer generally <1 m thick of variably muddy, shelly, glauconitic calcsand and calcirudite which, containing pedogenic and other clasts eroded from the seabed substrate, is itself a palimpsest deposit.

5.11.8 The continuing cycle of terrace formation and modification

Described above are some of the effects on the Kimberley shoreline-shelf-upper slope system of just one complete glacio-eustatic sea-level cycle. Such a cycle, however, is only a small part of an interactive sedimentary-tectonic-eustatic system that has been operating throughout the Quaternary. The deepest conspicuous palimpsest terrace imaged on the seismic profiles across the flanks of the Browse Sea-valley lies at a depth of ~200 m (215 ms TWT; Figure 5.11). Projecting a subsidence rate of 15 cm/ky to this depth gives an age of 1.33 Ma for the time of its primary formation.

The description in section 5 above applies closely to the Kimberley Shelf today, in its Holocene highstand setting. During such highstands, the inner part of the Kimberley (and Sahul) system is associated with the formation of a new primary depositional coastal plain-shoreface-inshore sediment prism terrace, whilst on the offshore shelf and upper slope occur a series of drowned terraces of analogous

primary highstand origin but of increasingly poly-palimpsest origin the further offshore and deeper the waters in which they are located.

Bathymetric terraces occur on the slopes of the Browse and adjacent sea-valleys down to at least 300 m (Figure 5.11), and the deepest-rooted corallgal shoals at the outer edge of the larger Bonaparte Shelf rise from slope depths of 350 to 400 m (van Andel and Veevers, 1965; Heyward et al., 1997). Extrapolating again a subsidence rate of 15 m/100 ky, back in time therefore suggests an origin for the Sahul Platform-edge reefs in the Late Pliocene at ~2.33-2.66 Ma. It may not be coincidental that this time corresponds with the global climatological change that accompanied the onset of the severe Late Cenozoic glacial cycles and northern hemisphere glaciation.

There is no doubt that “drowned” fluvial features occur on the terraced Sahul platform, and that subaerial processes therefore played a strong role in shaping it. But in allocating a non-marine origin to the platform, earlier writers have in general failed to make a clear distinction between pedogenic and fluvial features which were formed either (i) on a coastal plain which has since subsided, or (ii) near their present level, on a plain which was emergent during recent lowstands of sea-level.

The subaerial physiographic and pedogenic features preserved on the shallow Sahul Shelf are both relict and palimpsest, and many were formed during the MIS 2 sea-level low (Yokoyama 2001). At this time, the shelf comprised an arid coastal plain, with ponded drainage which converged into the Bonaparte

Depression or - locally and sometimes only at particular intermediate sea-levels - was passed over the shelf-edge through canyons such as the Penguin Deeps and the Malita Sea Valley and other channels. A similar arid coastal plain at the LGM has been proposed for the Great Barrier Reef shelf (Woolfe and Larcombe 1998; Woolfe et al. 1998), where there is, however, only minor evidence for channels which directly accessed the slope at lowstand (Blakeway 1991).

An alternative explanation for the relict interpreted fluvial features on the Sahul Shelf, preferred by most previous writers is that they formed on an older coastal plain which has since subsided to its present level. Such an interpretation, however, requires impossibly high rates of subsidence if it is to apply to the general (sub-Holocene) surface of the inner shelf. Note too that the larger offshore physiographic features, including the Sahul, Londonderry and van Diemen Rises, have been shown by Veevers and van Andel (1967) to be a manifestation of regional basement structure. Their origin, therefore, is deep-seated, and their morphology will have been shaped throughout succeeding glacial cycles, the last of which has been MIS 2. The sub bottom profiling acquired for this study demonstrates that features as deeply incised as the Penguin Deeps and probably the Malita Shelf-channel have been active through at least the last several glacial cycles. That probability notwithstanding, the surficial features of the Sahul Shelf were most recently shaped by subaerial processes during the last glacial lowstand, after which they have been blanketed by a thin veneer (<1m thick, except in peri-shoal sediment aprons) of palimpsest carbonate sediment offshore, and by a thicker (up to 10 m or more) sometimes patchy near-shore prism of modern terrigenous-carbonate sediment.

5.12 Sea level at the Last Glacial Maximum (MIS 2)

Most earlier writers have interpreted terrace and riser features on the Sahul Shelf in the 90-110 m depth range as marking the lowstand shoreline at the last glacial maximum, MIS 2 (Fairbridge, 1953; van Andel and Veevers, 1967). With the benefit of sub-bottom profiles (Figures 5.10, 5.11, 5.12, 5.13), and bearing in mind the interpretation outlined above, it is now apparent that most of the terraces and risers at these depths are poly-palimpsest and were initially formed at much shallower depths. The cemented, algal or coral-encrusted terraces of the deeper water Sahul Shelf were probably resistant enough to survive through several subaerial-marine eustatic cycles. Unless cemented at an early stage, such survival is unlikely to be true for the prisms of unconsolidated clastic sediment which accumulate at lowstand shorelines and their adjacent coastal plain and inner shelf. Such clastic prisms, however, should they have survived to the present, are likely to give a better indication of the location of a recent lowstand shoreline than are terraces or their risers.

A somewhat deeper MIS 2 shoreline has been inferred by Yokoyama et al. (2001), based on a recent study of a suite of cores from the Bonaparte Depression. Using micropalaeontological characterisations of fully marine, shoreface and brackish environments, and a comprehensive set of radiocarbon dates, these authors inferred a depth of 125 m for the position of the peak MIS 2 shoreline. Whilst the Yokoyama et al. dataset is of high quality, and the interpretation they present is defensible, an alternative is possible. Once sea-level had fallen below about -100 m, the Bonaparte Depression received virtually all of the drainage from the emergent Sahul platform and its hinterland. The depression at that time comprised

a large restricted lagoon with a maximum depth of about 30 m and an estimated annual freshwater inflow (based on modern runoff estimates) equivalent to about 60% of its total volume (van Andel et al., 1967). Given that its only connection to the open ocean was through the narrow Malita Channel, and allowing for reduced precipitation during the glaciation, it seems likely that the Bonaparte Depression would have experienced periods of fully marine, brackish and (should the channel connection to the open ocean have been interrupted) perhaps even hypersaline conditions. Given these circumstances, the palaeo-environmental interpretations of Yokoyama et al. (2001) may have been overweighted, and the cluster of brackish water dates between 19.3 and 21.8 ka at ~120 m which form an important part of their MIS 2 sea-level estimate may bear no necessary relationship to the true open-coast sea-level. A second cluster of dates occurs between 17.4 and 19.0 ka at -100 to -110 m depth and are associated with shallow shoreface faunas, so an alternative interpretation of the Yokoyama et al. (2001) data is that the MIS 2 shoreline lay within or close to that shallower depth range. In this regard, it is relevant to note that, prior to Yokoyama et al.'s paper, one widely used estimate for the depth of the MIS 2 shoreline was -105 m (Peltier 1994).

There are three sedimentary prisms on the Kimberley outer shelf, A, B and C, which, together with their associated features, occur within the possible depth range of the MIS 2 shoreline (-100 to 150 m) and which are here interpreted as representing drowned clastic shoreline prisms. These prisms pinch out landwards at inferred shoreline depths of 108, 112 and 150 m respectively, and their stratigraphic relationships indicate that A is younger than B is younger than C.

According to most recent sea-level reconstructions such as those of Siddall et al. (2003), clastic prism C at -150 m is located too deep to represent deposition at the last glacial maximum shoreline. On the other hand, inferred shoreline prisms A and B lie at significantly shallower depths than the 120-125 m estimated for MIS 2 sea-level by Yokoyama et al. (2001), Siddall et al. (2003) and many other authors.

5.13 Discussion

In the absence of samples or numeric ages for prisms A, B and C, arriving at a unique interpretation for them is not possible, and most of the obvious alternatives have clear defects. For instance, one possibility is that prisms A and B relate to the successive MIS 2 and MIS 4 glacial periods. But why is the MIS 4 prism so much bigger? And if B is MIS 4, then C should be MIS 6, but it is 15 m too deep even after allowing for subsidence.

Yet 105-110 m would be consistent with some modern work, e.g. Peltier. Could the bathymetric features (Figure 5.11) be an estuarine lagoon and a 105 m shoreline? In judging final depth, calculations should allow 1 m tectonic and ~1m hydro-isostatic subsidence on the shelf edge and lesser landward.

Terraces will be nearer together when deeper (40 ky cycle), and their spacing may relate to the super-cycles on the global ice volume curve.

It is unwise to use a terrace level to pick the LGM lowstand, due to the adjacent, similar depth, palimpsest surfaces. Therefore it is imperative to use sediment

facies, and identification of the LGM inshore sediment prism. The upper of the two preserved in the Penguin Deep is 150 ms (113 m), and the next is close to 200 ms (150 m).

Note (i) 37 m separates them, which would be two subsidence cycles, and (ii) the upper one downlaps the lower and therefore must be younger. Could be retrogressional ISPs consequent upon post-LGM rise. Perhaps it is more likely they represent prisms deposited during the transgression, cf. GBR shelf (Dunbar et al., 2000)

For the reasons discussed above regarding sediment prism B, prism C (Figure 5.10) is interpreted as a relict inshore sediment prism deposited during a glacial lowstand. Assuming that prism B is correctly allocated to MIS 2, then prism C might represent either MIS 4 (~70 ka) or MIS 6 (~130 ka). Given the ~40 m difference in the depths of their respective clinoform breakpoints, and noting the likely subsidence rate here is ~0.15 m/ky, prisms B and C differ in age by about 260 ky. Assuming that prism B is correctly allocated to MIS 6, then prism C may represent MIS 8. If MIS 6, then subtract 15 m subsidence, subtract 10 palaeo-depth of outer edge, and shoreline is implied at 125 m.

But two certain conclusions from this chapter.

1. The previous recognised single shoreline at these depths is not a correct interpretation. Rather there is a platform and 2 apparent shoreface wedges, plus a third (deeper) wedge.

2. Neither the platform nor the two prisms lies at the accepted 125 m depth of the LGM shoreline.

Chapter 6 Summary

The Kimberley Shelf forms part of the wider Northwest Shelf of Australia, a peri-continental platform which stretches between Darwin in the northeast and Northwest Cape. The oceanward edge of the Bonaparte Shelf is termed the Sahul Shelf, and it is located at relatively shallow depths of 110-130 m, and though bathymetric highs along it today support corallgal reefs, these were destroyed and the shelf edge exposed during late Pleistocene glacial lowstands. The Kimberley Shelf coastline is regionally embayed towards the southeast, creating the Joseph Bonaparte Gulf, into the southeastern corner of which flow the Ord, Victoria and other smaller rivers. These are the main source of terrigenous sediment for the nearby shelf.

Bonaparte Gulf waters merge offshore into those of the Timor Sea. Their hydrography is influenced by the effects of the oceanic Indonesian Throughflow Current which flows southwest along and outside of the shelf edge, by extremely strong tidal streams which occur especially around the Admiralty Bay-Kimberley region, and seasonally by the passage of cyclones.

In addition to control by sea-level and subsequent reef development, powerful hydraulic forces which drive current speeds of 50-100 cm/s or more, affect sediment transport and deposition throughout Australian marine carbonate provinces. Such controls include exposure to storms and swells, tropical cyclones, exposure to major ocean currents and tides. The precise agent differs from place to place, outer shelf carbonate platforms throughout Australia, are often characterised by the bypassing of sediment along-shelf or over nearby shelf edges. When the processes of sediment accretion, cementation are out preformed by erosion on carbonate shelf environments, it produces what has been termed by James et al (1994), as a 'shaved shelf'. Consequently, these bioclastic carbonate sediments with a low or condensed sedimentation rate are often also palimpsest in nature.

The Bonaparte Shelf carries a thin Holocene sediment cover with projecting corallgal reefs (van Andel, 1965; van Andel and Veevers, 1965, 1967). The 120 m-deep linear feature the Penguin Deeps, cuts along the northern Kimberley Shelf. It does not connect back to the shoreline, and at present sea level is a drowned and largely inactive shelf-valley system. The inner (eastern) entrance to the Penguin Deeps lies near the -60 m isobath, so when in the recent past (e.g. at times during climatic cycle MIS 1-5) sea-level was slightly lower than this, the Penguin Deeps will have been flooded with marine waters, subjected to strong tidal currents and probably operated as an important supply channel for sediment passing westward from the Bonaparte Shelf and into the Browse Sea-valley. However, phases when the Penguin Deeps operated as a sediment conduit in this fashion were mostly short-lived, because its eastern portal lies at ~100 m-depth. 18-20 ky ago, during the peak of Marine Isotope Stage 2 (MIS 2), the shoreline was probably located a little deeper than this and up to 30 km seaward of the western end. At this time, it was cut off from the sea, and became a seasonally-controlled fluvial and lacustrine canyon.

Once the rising postglacial SL reached ~-70m, the Penguin Deeps conduit starts to become important in focusing waters off the shelf to the west. The bathymetry of the Bonaparte Shelf indicates that with SL at -70m, fluvial systems had an additional way to drain, than to the north via the Malita sea way. The Penguin Deeps directed waters not only from the Ord and Berkeley rivers, as it does at times of low SL, but at times of higher SL, potentially from the entire Joseph Bonaparte Gulf.

Subsequently, when SL is >-70m, the Penguin Deeps plays a larger role in the redistribution of both the fluvial derived sediments and the biogenic, and reworked sediments from the Bonaparte Shelf. It is anticipated that the new regional hydrological regimes become established as SL floods the continental shelf. In the initial stages of the new hydrological regime, erosion and subsequent deposition rates are thought to have been high. This occurs as the inundated shelf environment provides an efficient medium whereby sediments of all sizes can be

transported not only by tidal and current regimes but at times of dynamic storm and cyclone activity.

It is probable that a thin layer of soil developed over the exposed shelf during the LGM, on top of Pliocene / Pleistocene carbonates. The shelfal material, subsequently transported into the depression of the Malita Shelf Valley, would have been subject to immediate reworking, erosion and deposition once the rising sea level inundated the Bonaparte Shelf, early in the Holocene. Much of the calcareous biota growing on the shelf when SL was ~-50, was almost simultaneously eroded across the shelf environment during the rising sea level. During the LGM sea levels, much of the shelf sediments would have initially transported northwards out the Malita shelf valley and other cross shelf drainage channels to the north and north west, either as resuspended sediments, or as bed load.

Locations not previously considered by earlier sedimentologists were targeted in the acquisition program of this study. Despite being a region of high economic interest due to the occurrences of hydrocarbons, no other sampling program has investigated this basin boundary in a recent geological historical context. The result of a series of marine sediment sampling and seismic surveys for this thesis allows for a complete seamless surficial sedimentological study of the NW shelf from the Browse across to the Bonaparte shelves which up until now was incomplete

For the purposes of this work three subdivisions of the Kimberley Shelf are recognised, namely an *inner shelf* 0 - 50 m isobath (corresponding approximately to the offshore edge of the terrigenous ISP inshore sediment prism), a *middle shelf* between 50 and 105 m depth (a current-swept, sediment-starved plain), and an *outer shelf* between 105 and 150 m depth (corresponding to areas of deeper terrace). For descriptive purposes, the Kimberley Shelf terraces are referred to in terms of the estimated depths of their seaward edges, the most widespread ones being the 30 m-, 45 m-, 60 m-, 75 m-, 95 m-, 112 m-, 165 m- and 185 m-terraces.

Subsidence rates based on these descending flight of terraces and the regional rates suggests a rate of 15cm/ka at least for the late Quaternary.

Both bathymetric and Landsat TM images contributed to the regional perspective by providing evidence of morphological and sediment distribution and the direction of mobilisation (Chapter 2.5.2). Recent work on the development of the shelf edge bioherms (Chapter 2.2.2) and the infilling of the Ord River dam assisted in the both the assessment of the regional sediment contribution rates and their provenance (Chapter 2.6). Regional climate observations give insight to the changes in vegetation patterns (Chapter 2.7) and indicate that the occurrences of cyclones play an important role (Chapter 2.4.3) in the distribution and perhaps the sediment provenance.

With regional subsidence rates >15cm/ka the Bonaparte Shelf edge is a productive carbonate factory and several corallgal bioherms maintain their position within the photic zone. These are termed the Sahul Banks.

All of the gravity cores taken across the Penguin Fan and the Browse Sea Valley contained sediments that were Holocene age or older and had accumulation rates range from 16.8 – 223.2 cm/ka. This indicates a layer of sediment deposited during the Holocene of ~5m deep across the Browse Sea Valley (75 X 100km or 60.5 X 100km) potentially exists. This implies that 30 - 35 km³ of sediments has been introduced to the accumulation area over the past 11 ka.

Sediment meters deep	Browse Sea Valley area 6 050 000 km ²	Browse Sea Valley area 7 000 000 km ²
4	24.2 Km ³	28 Km ³
5	30.25 Km ³	35 Km ³
6	36.3 Km ³	42 Km ³

Table 6.1 The potential amount of sediment deposited in the Browse Sea valley during the Holocene.

Fluvial derived terrestrial sediment yields for the northeast Kimberley block during the Holocene are estimated to be $63 \text{ tonnes} \times 10^9$. For the Ord river alone 42.28 km^3 of sediment volumetrically (based on a SG of 1.49) for the Holocene or 18×10^9 (12.05 km^3) over the past 6 ka, during which time there has been negligible change in marine or climate regimes.

This study reveals that sea level change, cyclones, modification to monsoonal influences, wind patterns and oceanography have all contributed to variation in the terrace construction / destruction, sediment provenance, deposition styles and locales over time. The thesis identified these processes as; Sea Level and climate change, cyclone activity and ocean currents, and revealed their impact on the geologically recent sediment distribution over the Kimberley Shelf.

A primary finding of this study was that the water currents across the Bonaparte Shelf have changed with the influx of water onto the shelf at times of higher sea level. This southerly and then westward flowing current may be the very erosional agent that formed the Penguin Deeps itself, and over time the conduit channelled sediments off the shelf forming the Browse Sea Valley deposit.

Chapter 7 Conclusions

The conclusions of this thesis are based, in part, on the geochemical analysis of 48 surficial sediment samples, sub-bottom profiling and the collection of 15 gravity cores over the Kimberley Shelf and Browse Sea Valley. The subsequent geochemical data from these samples yields insight to the types of change and rates of change over the recent past.

The physical and geochemical sediment description and analysis indicated a record of limited productivity of biogenic sediments during the Holocene and assisted in identifying the origin of relict and palimpsest shelf facies. Much of the sediment was reworked older shelfal sediments, mainly foraminifera and comminuted biogenic carbonates from towards the shelf edges, and muds, calcareous algae, Bryozoan hash and solitary corals from within the Bonaparte Shelf basin and near shore environments. These sediments are characterised by degrees of staining and abrasion indicative of exposure during sea level low stands and transport respectively.

This work has also identified that the water currents across the Bonaparte Shelf change with the influx of water onto the shelf at times of higher sea level, with changing prevailing winds and cyclone activity. These forces significantly impact on the distribution of sediments across the Kimberley Shelf and into the Browse Sea Valley.

Sub-bottom profiling demonstrated that the Browse Sea Valley is a site of accumulation over geological time. The successive sets of sediment packets deposited on rising and falling sea levels have been deposited over at several sea level oscillations.

The significance of the findings in this study highlight the rates of change on a tropical carbonate dominated shelf, shelf edge and slope. It reveals the dynamic relationship of limited recent sediment production, effective sediment transport

regimes and areas of sediment accumulation. The sediment is both biogenic and terrestrial derived and the accumulation sites change with variation in oceanography and climate.

Therefore, this work has direct relevance to Australian bio-regionalisation studies and to the evaluation of sites for off shore construction and the viability / security of positioning submarine assets in this environmentally and internationally sensitive, bio-diverse, resource rich environment.

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Appendix 2.1

The translation for the text on the map states;

“Some people believe that Marco Polo discovered the land of Lochacin this region and, proceeding 500 miles, Penta Island and the Malaiur Kingdom are found. Very little is known of them and apart from the reports of med.la. c.8. e,g. by Ramusio in the 2nd volume, many modern authors have ignored them in their tables. Abbot Boudrand included them among the fictitious country in opposition to the P.D. Vital Red Land.”

‘Land of Concord discovered in 1618’

Translation courtesy of Dr. Laura Sbaffi

Appendix 2.2

Contributors to the Bathymetric data base

1. Ampol Exploration Ltd;
2. Ampolex Ltd;
3. Antarctic Support Associates;
4. Atlantic Richfield Company;
5. Australian Hydrographic Service;
6. Australian Surveying and Land Information Group;
7. BHP Billiton;
8. British Oceanographic Data Centre;
9. British Petroleum;
10. Bundesanstalt für Geowissenschaften und Rohstoffe;
11. Bureau of Resource Sciences (Australia);
12. Canada Northwest Oil (Australia) Pty. Ltd.;
13. Canadian Occidental Petroleum Ltd;
14. Canyon Oil;
15. Carnarvon Petroleum Pty Ltd;
16. Centre for Resource and Environmental Studies ;
17. Chevron Corporation;
18. Commonwealth Scientific & Industrial Research Organisation;
19. Conoco Inc.;
20. Cultus Petroleum NL;
21. Dept. Science, Industry and Resources (NZ);
22. Division of National Mapping (Australia);
23. Elf-Aquitaine;

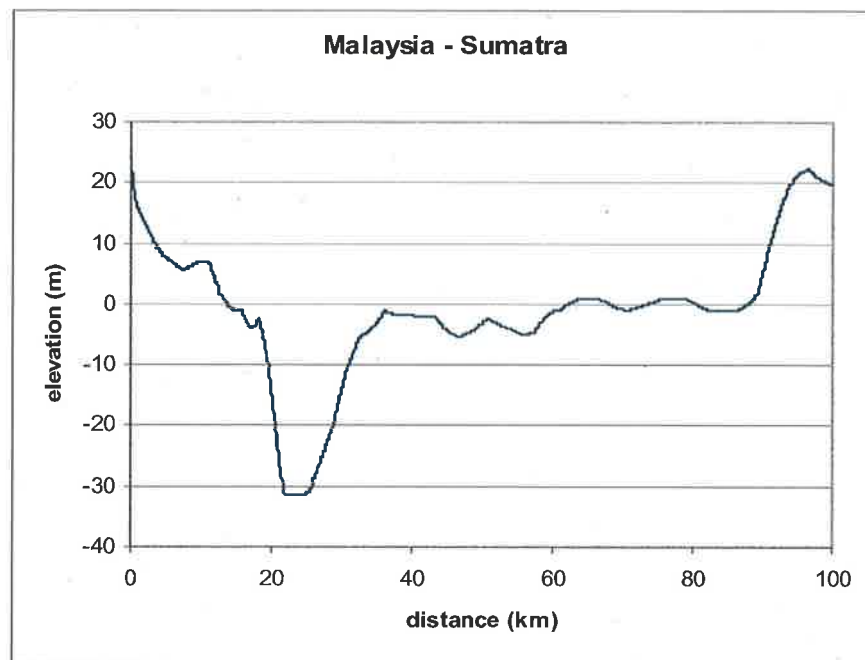
24. Enterprise Oil Exploration Pty. Ltd.;
25. Esso Australia Ltd;
26. Flinders University;
27. French Institute for Polar Research and Technology;
28. Geophysical Services International;
29. Geoscience Australia;
30. Getty Oil;
31. Globex Resources Ltd;
32. Great Barrier Reef Marine Park Authority (Australia);
33. Gulf Oil;
34. Hadson Oil;
35. Haliburton Geophysical Services International;
36. Hudbay Oil & Gas;
37. Institut de Recherche pour le Developpement;
38. Institut Francais de Recherche pour l'Exploitation de la Mer;
39. Institute for Polar Research (Japan);
40. Institute of Oceanographic Sciences, UK;
41. Japan National Oil Corporation;
42. Japan Oceanographic Data Centre;
43. Kuwait Foreign;
44. Petroleum Exploration Company;
45. Lamont Doherty Geophysical Observatory;
46. LASMO plc;
47. l'Observatoire Oceanologique de Villefranche-sur-Mer;
48. Marathon Oil;

49. Mimpex Ltd;
50. Minerals & Energy South Australia;
51. Minora Resources NL;
52. Mobil Corporation;
53. National Environmental Research Council (UK);
54. National Geophysical Data Centre (USA);
55. Nopec International;
56. Norcen Energy Resources Ltd.;
57. Ocean Drilling Program;
58. Outback Oil N.L.;
59. Petrofina Exploration;
60. Phillips Oil Company Australia;
61. Primary Industries and Resources South Australia;
62. Russian Scientific and Research Institute for Geophysics;
63. Sagasco Resources Ltd;
64. School of Ocean and Earth Science & Technology;
65. Scripps Institution of Oceanography;
66. University of California;
67. Seafield Resources Plc.;
68. Shell Development (Australia) Pty. Ltd.;
69. South Australia Department of Mines & Energy;
70. Stirling Petroleum;
71. Strata Oil;
72. Target Oil;
73. Texas A & M University;

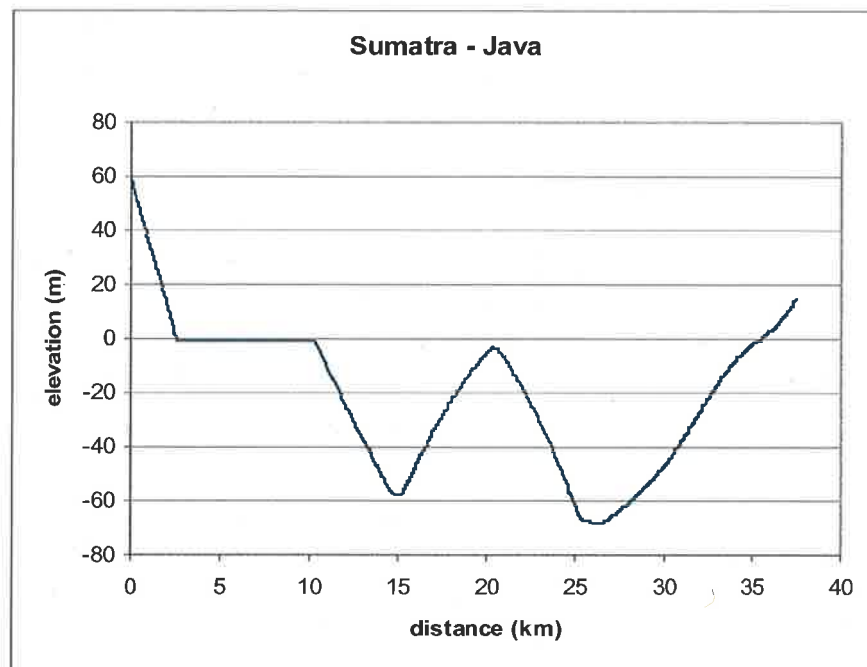
- 74. Ultramar Australia Inc.;
- 75. United States Geological Survey;
- 76. University of Adelaide;
- 77. University of Tokyo;
- 78. US Navy;
- 79. Wainoco International;
- 80. West Australian Petroleum Pty. Ltd.;
- 81. Western Geophysical;
- 82. Western Mining Corporation;
- 83. Woods Hole Oceanographic Institute;
- 84. Woodside Offshore Petroleum Pty. Ltd.

Appendix 2.3 Profiles of the gateways of the Indonesian Throughflow.

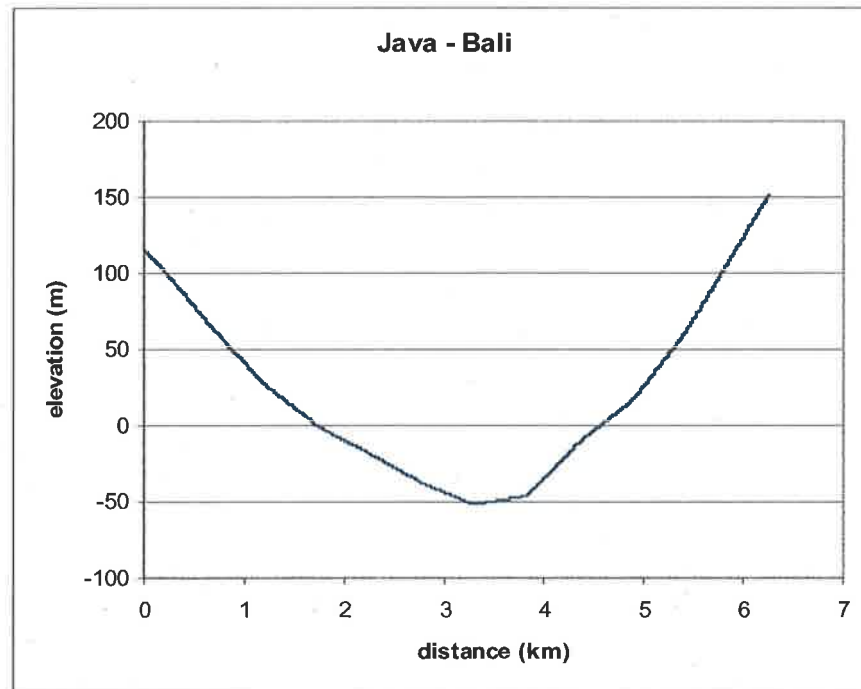
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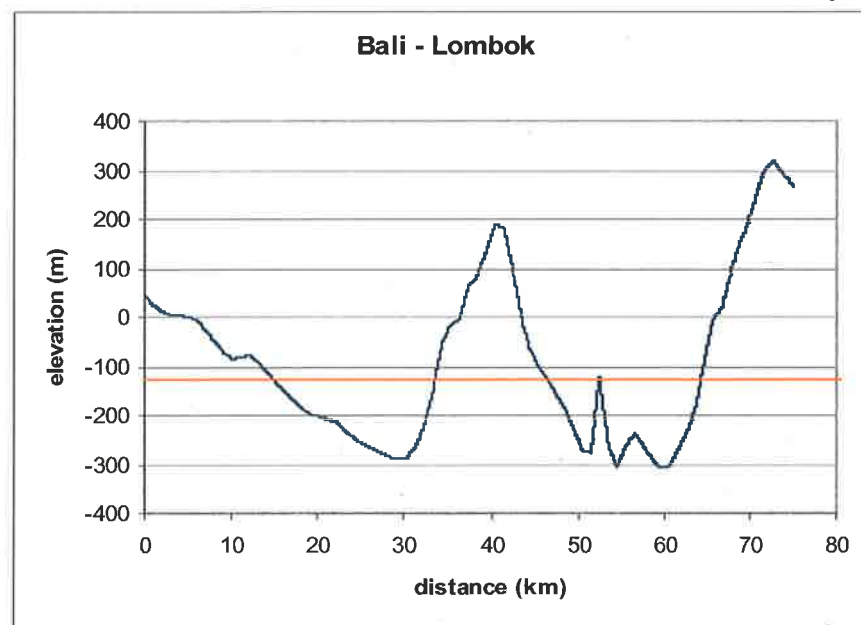
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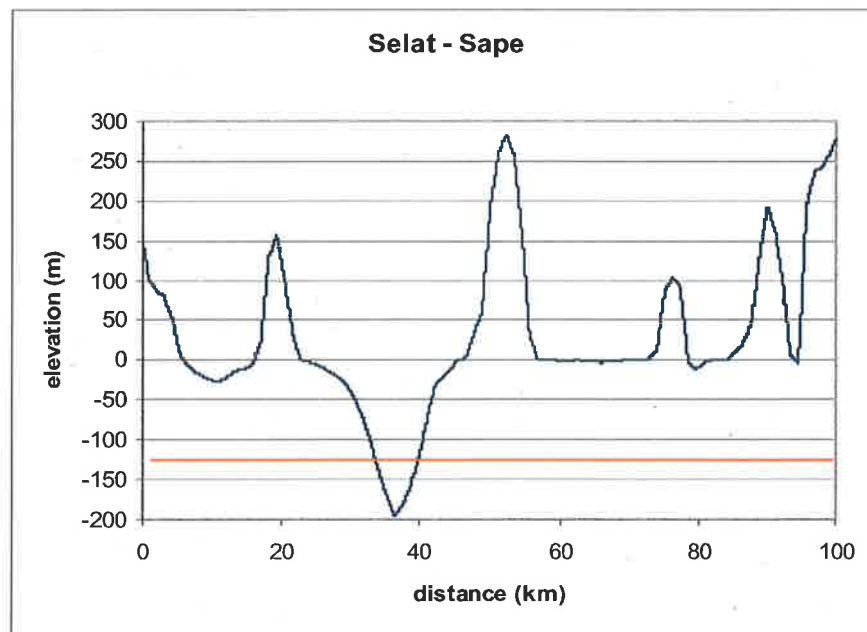
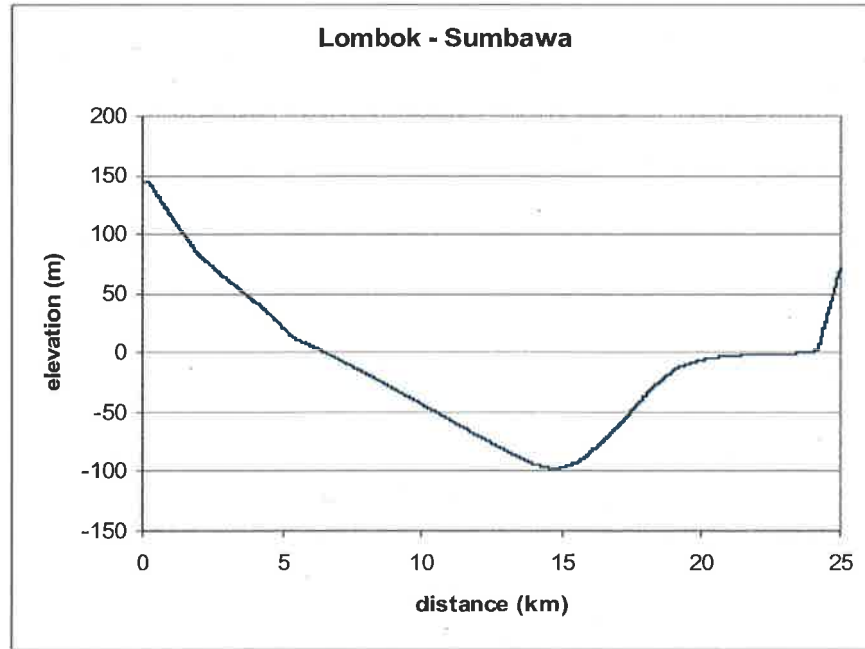


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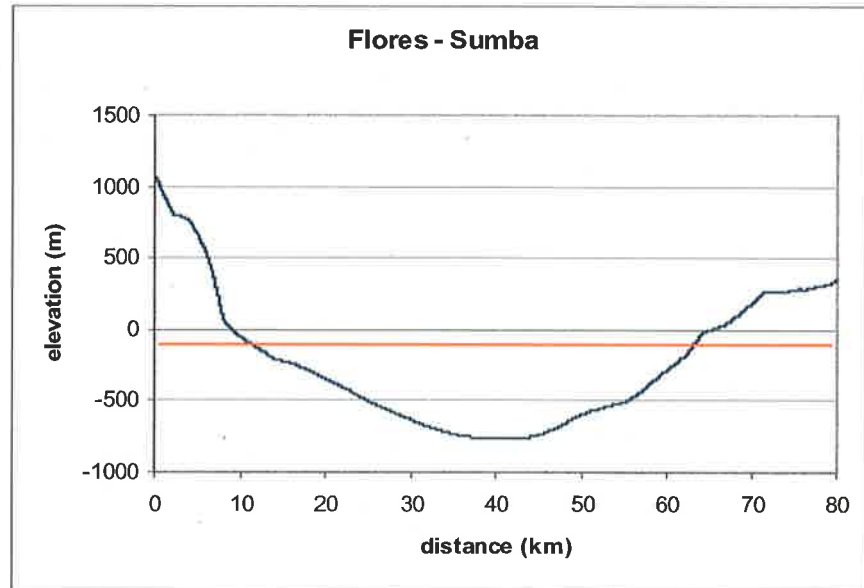


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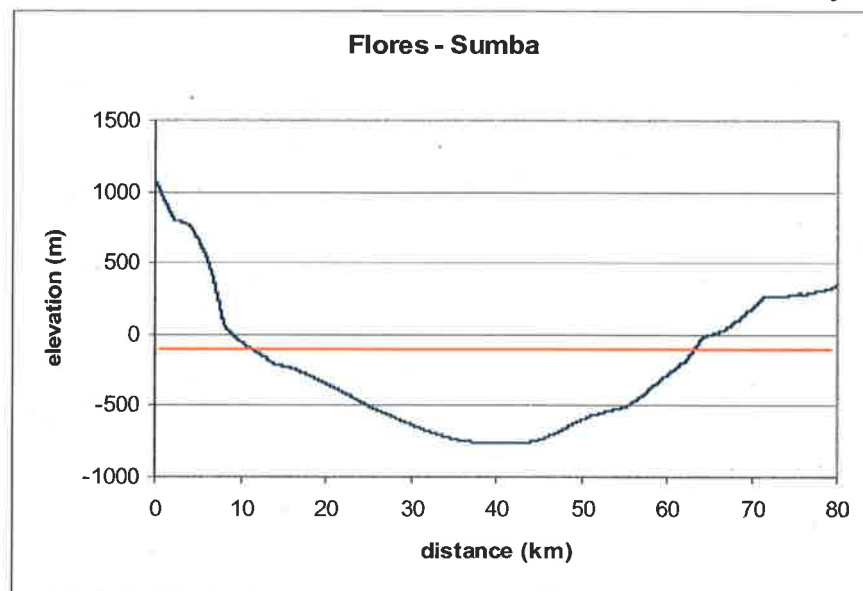




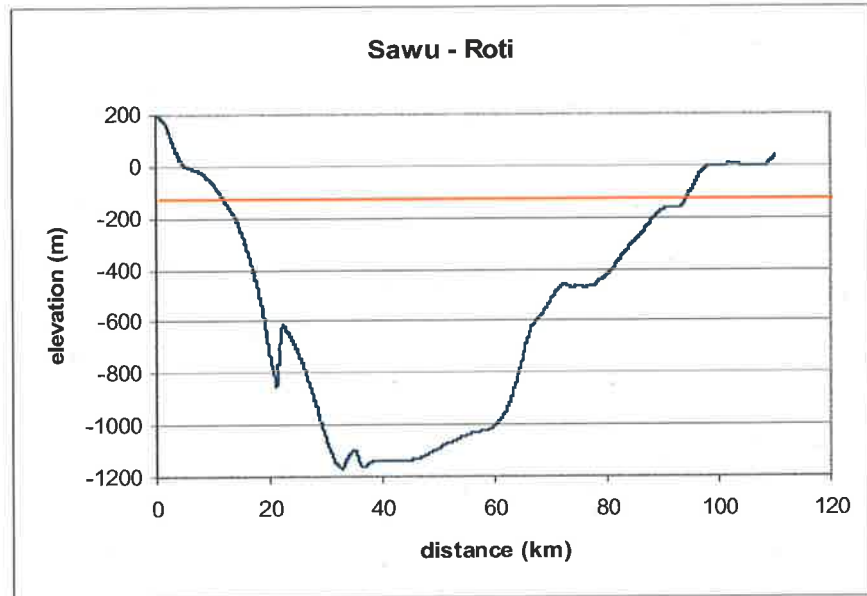
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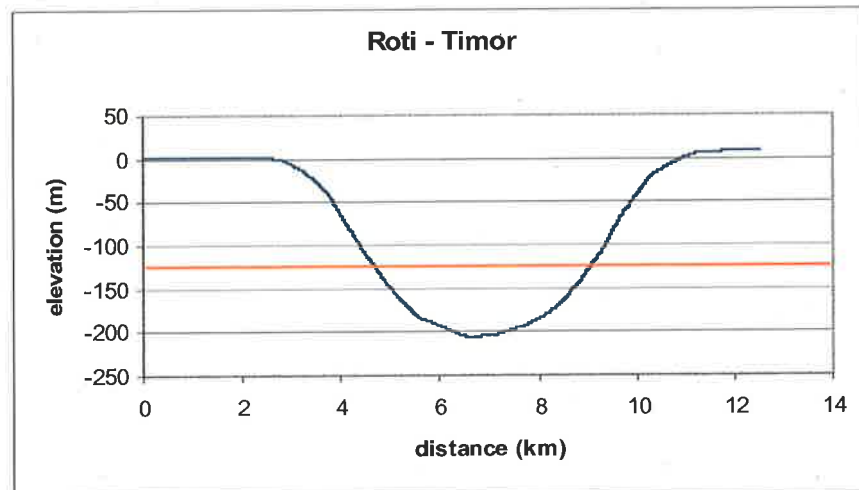
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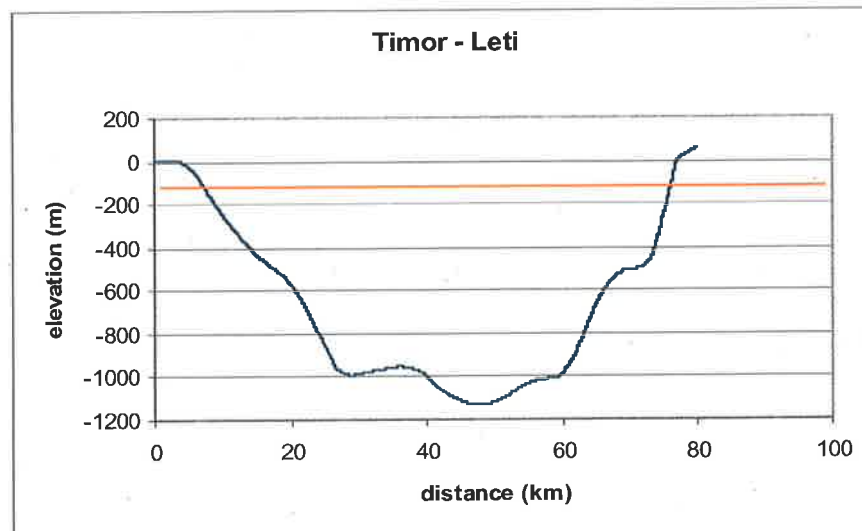
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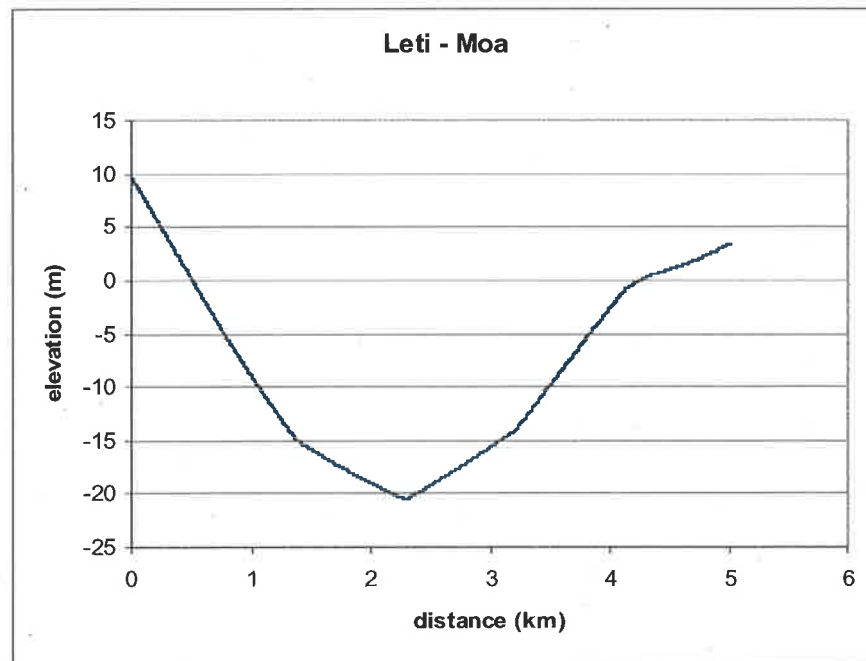
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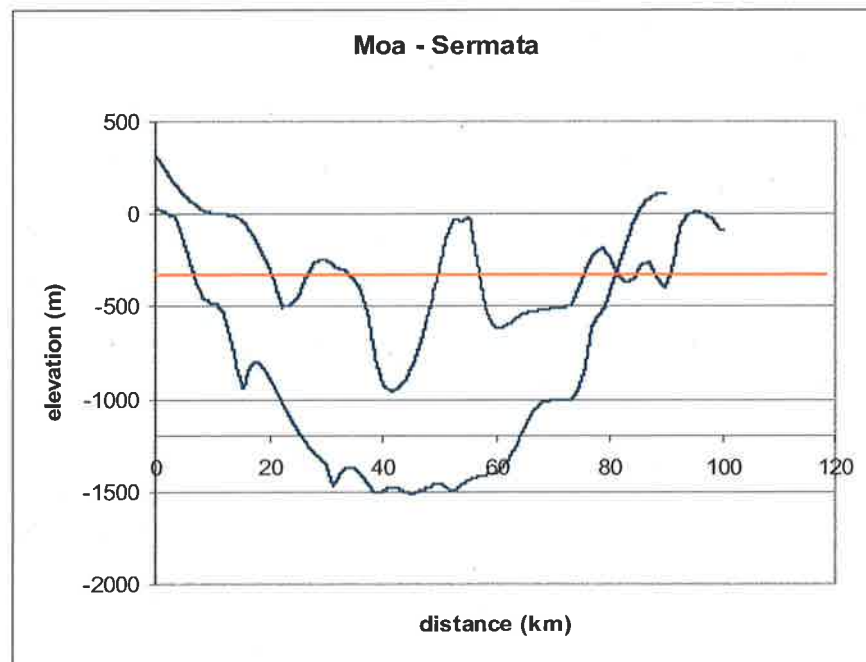
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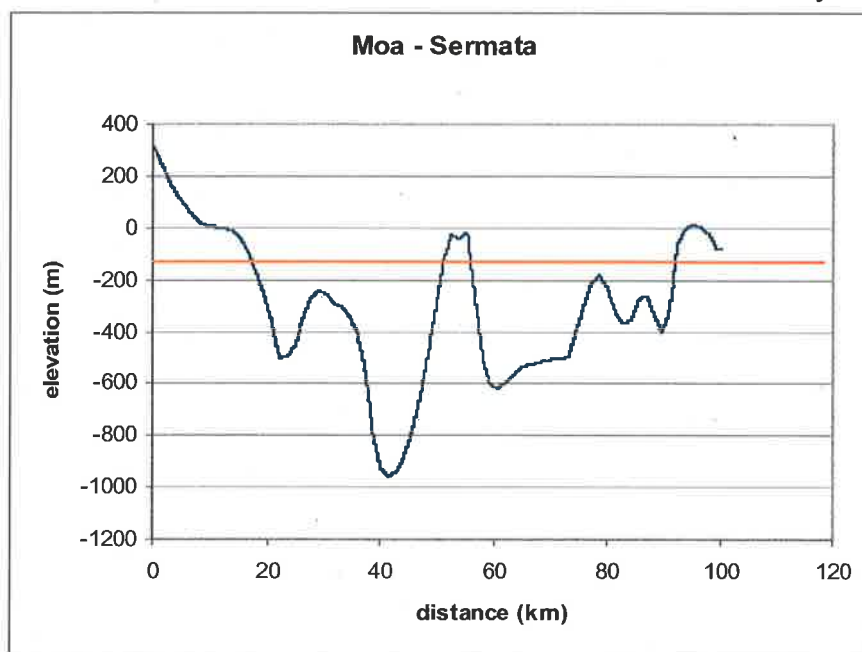
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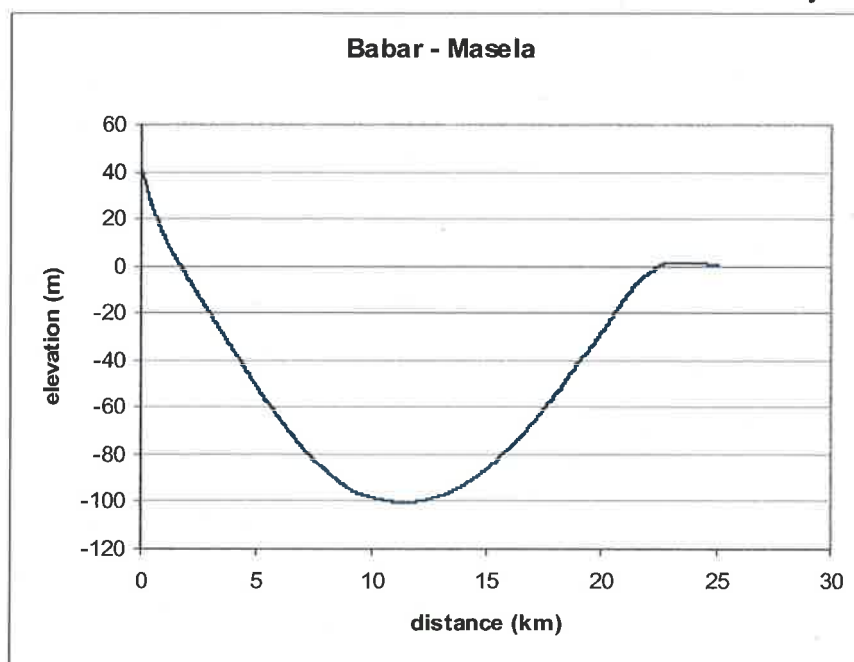
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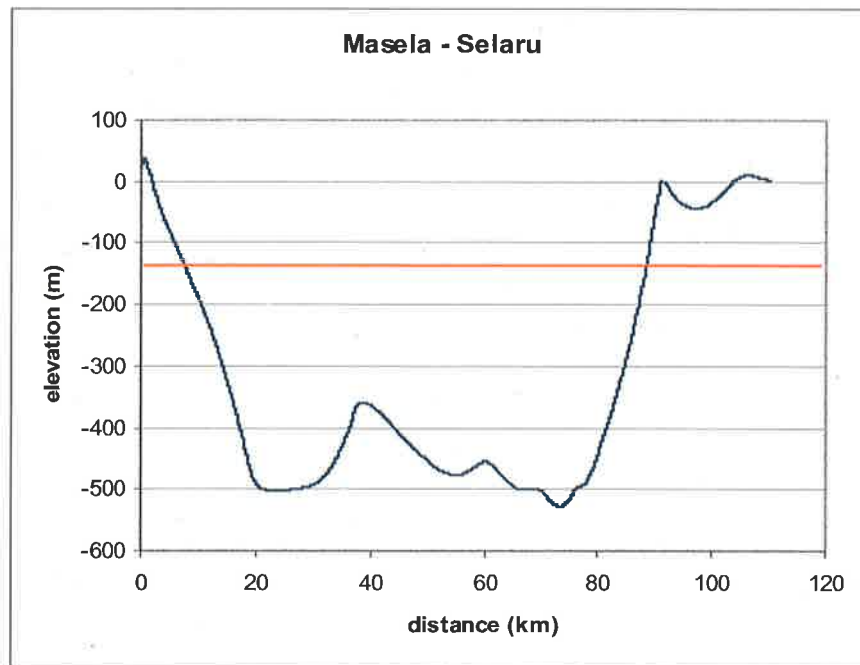
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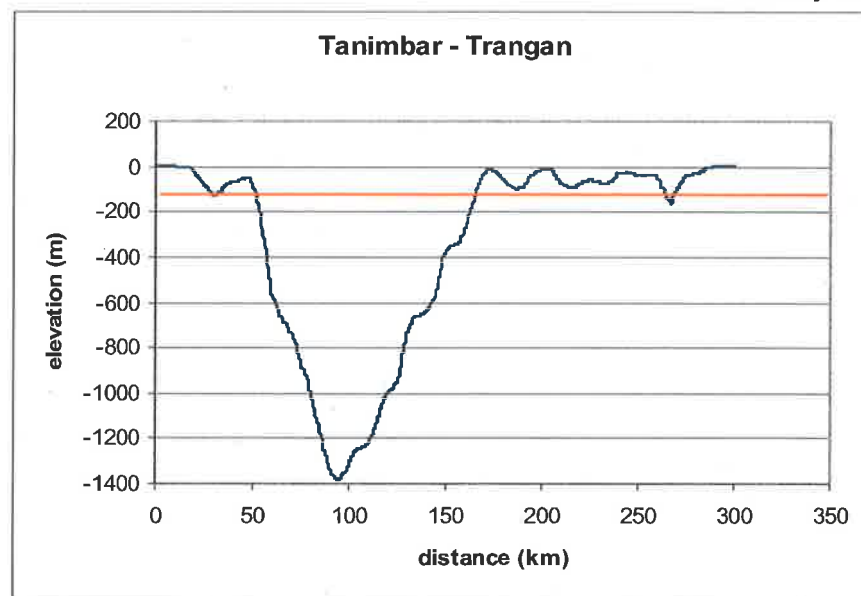
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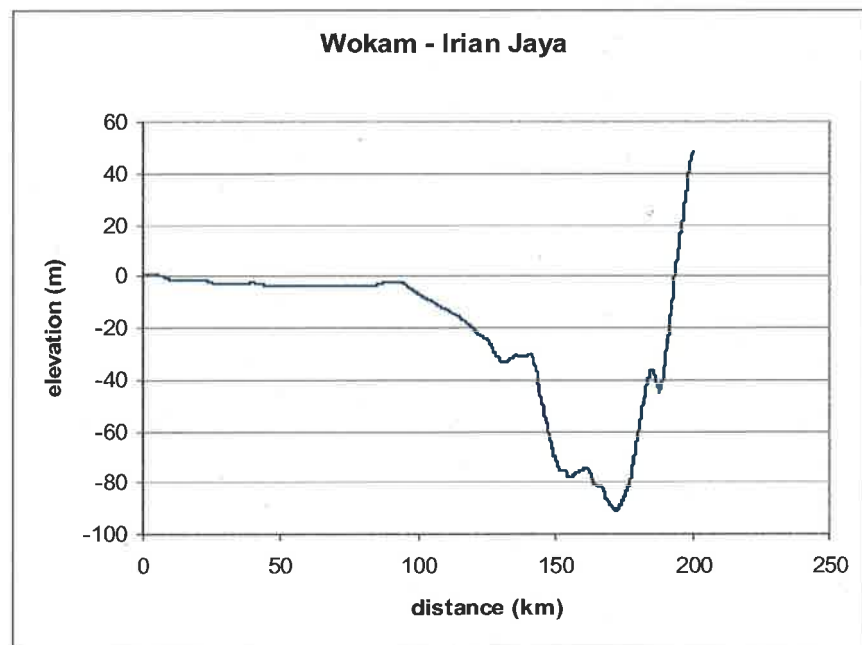
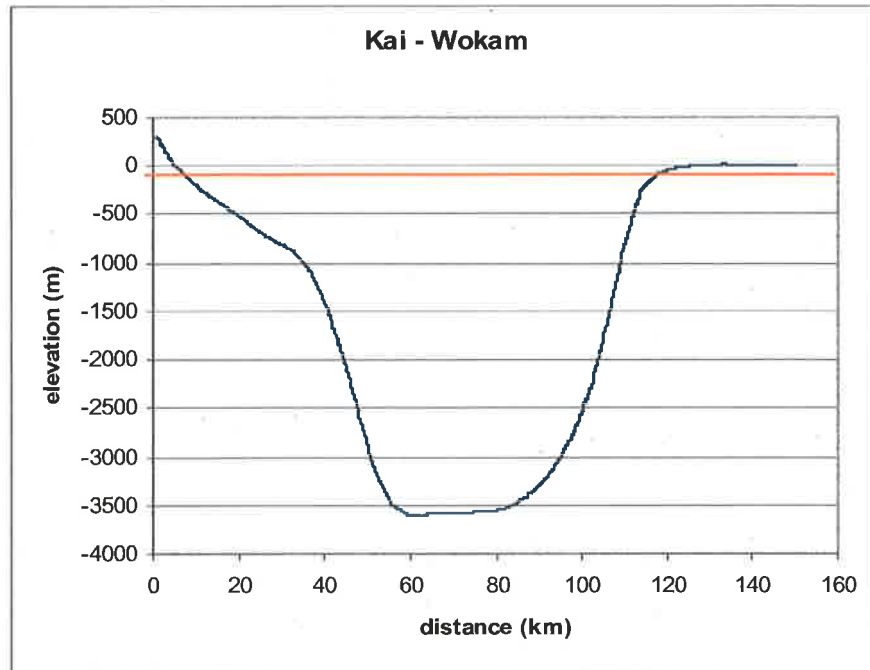


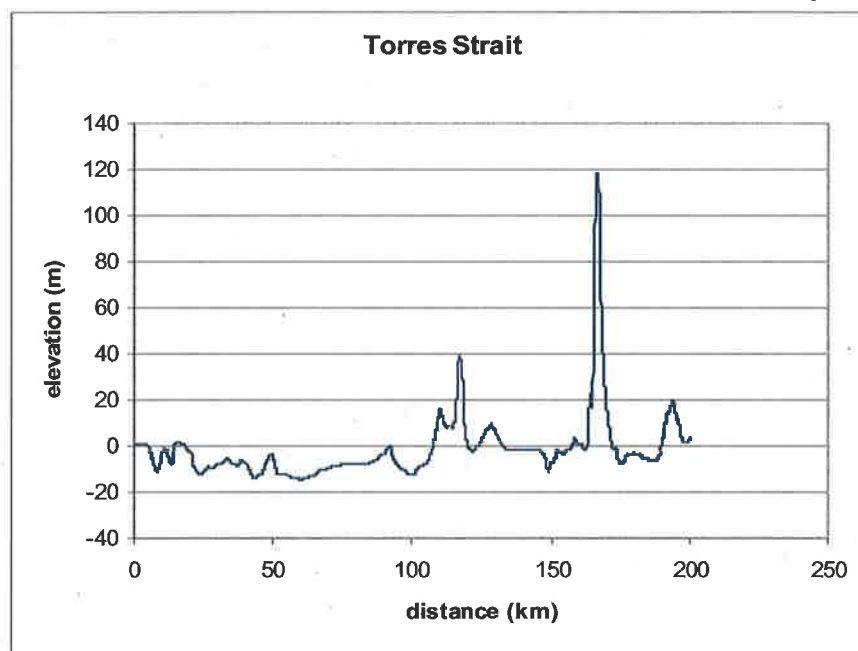
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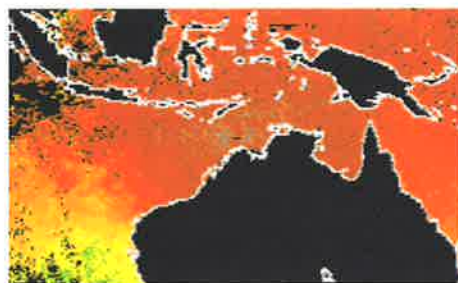
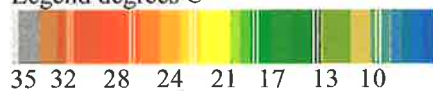




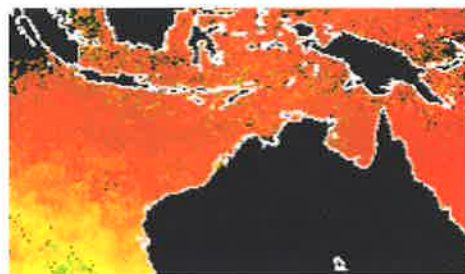
Appendix 2.4

The regional sea surface temperatures from Bureau of Meteorology Australia

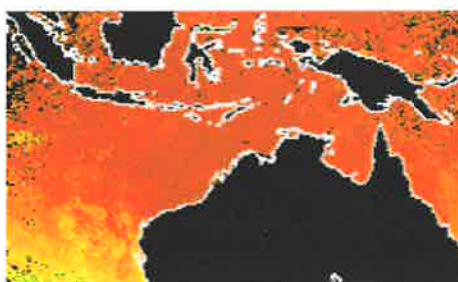
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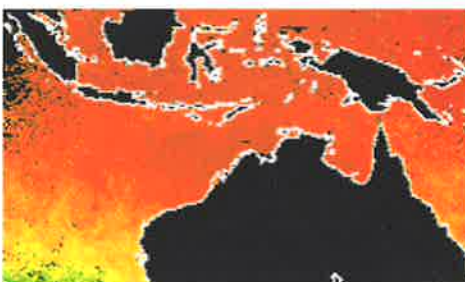
Jan 2002



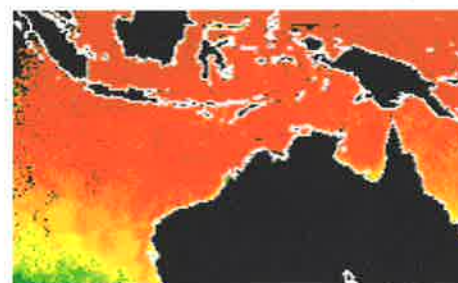
March 2002



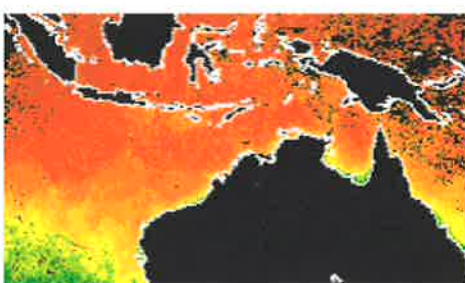
April 2002



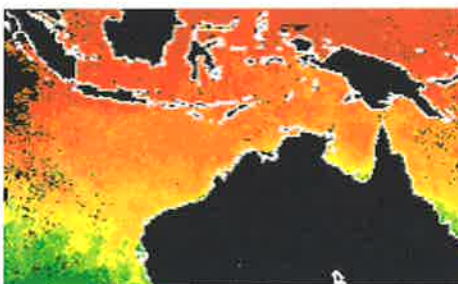
May 2002



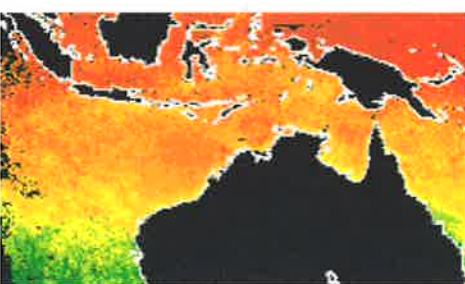
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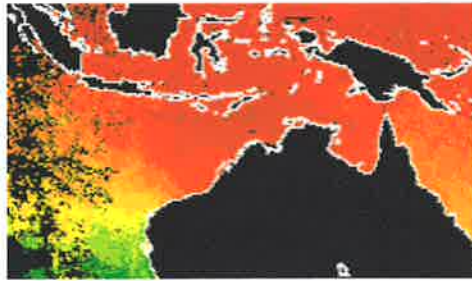
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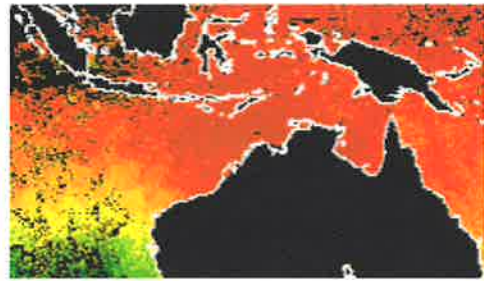
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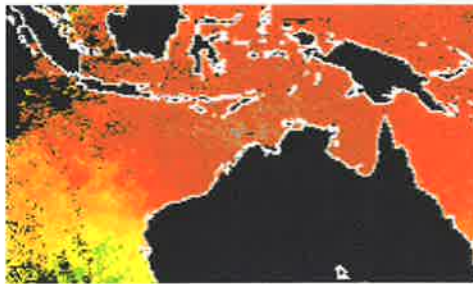
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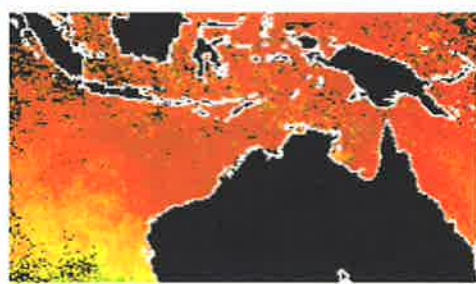
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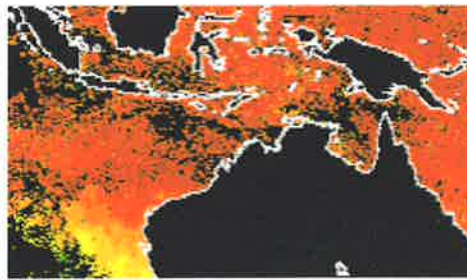
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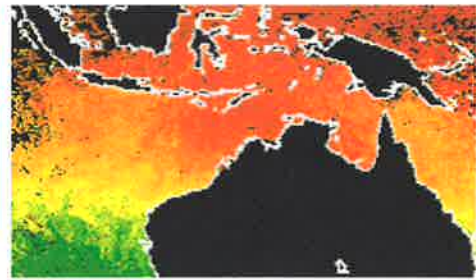
January 2003



February 2003



March 2003



October 2003

Appendix 2.5 Rivers and creeks of the western Joseph Bonaparte Gulf.

Estuary Id	Estuary Name	State	Latitude	Longitude	Catchment area	Extreme tidal range
W126	KING EDWARD RIVER	WA	-14.20341	126.5857	9002	4.8
W127	MISSION COVE	WA	-14.11732	126.69829	170	4.8
W128	DRYSDALE RIVER	WA	-13.94824	126.80321	15106	4.8
W129	un-named	WA	-13.77398	126.833	261	4.8
W130	un-named	WA	-13.74878	126.90494	134	4.8
W131	un-named	WA	-13.87954	127.07959	668	3.9
W132	un-named	WA	-13.94665	127.20345	96	3.9
W133	KING GEORGE RIVER	WA	-13.96172	127.32261	2776	3.9
W134	un-named	WA	-14.06288	127.45329	157	3.9
W135	BERKELEY RIVER	WA	-14.34303	127.78032	5149	3.9
W136	un-named	WA	-14.44262	127.83164	115	7.8
W137	un-named	WA	-14.59212	127.95968	547	7.8
W140	THOMPSON RIVER	WA	-14.95918	128.11526	167	7.8
W141	ORD RIVER	WA	-15.04492	128.14864	85213 or 88150	7.8
W139	LYNE RIVER	WA	-14.867	128.14999	335	7.8
W138	HELBY RIVER	WA	-14.74088	128.18678	105	7.8
W142	un-named	WA	-14.9031	128.34363	2298	7.8
W143	un-named	WA	-14.77217	128.52301	81	7.7
W144	un-named	WA	-14.78896	128.60553	176	7.7
W145	un-named	WA	-14.82533	128.74309	355	7.7
NT001	un-named	NT	-14.88449	129.04529	100	7.7
NT002	KEEP RIVER	NT	-14.93603	129.19374	7495	7.7

Data obtained from the OzEstuaries data base www.ozestuaries.org.au August 2001

Appendix 3.1 Sediment sample analysis

Sample No	Sample	Aquisition method	Survey	South	East	Latitude	Longitude	Total Organic Carbon	CaCO3	Colour	Water Depth	Core Depth	Gravel	Sand	Mud	Fresh Sand	Inter-mediate Sand	Relic sand	Fresh Gravel	Inter-mediate Gravel	Relict Gravel
6401603	AGSO 01	SM001	s225	13°23.113	126°27.671	-13.384463	126.456710	0.19	22.50	5y 5 2	83.60		2.48	64.58	32.94	33.00	55.00	12.00	20.00	20.00	60.00
6401604	AGSO 02	SM002	s225	13°23.667	126°18.887	-13.390003	126.308870	0.28	50.00	5y 5 2	155.20		10.22	42.93	46.85	25.00	60.00	15.00	0.00	53.00	47.00
6401605	AGSO 03	SM003	s225	13°12.5318	126°03.58	-13.205318	126.055800	0.11	85.00	2.5y 5 4	27.60		29.06	65.42	5.52	20.00	20.00	60.00	0.00	10.00	90.00
6401606	AGSO 04	SM004	s225	13°18.5308	126°02.28	-13.305308	126.036133	0.26	80.00	2.5 6 2	92.00		0.00	0.00	0.00	0.00	40.00	60.00	0.00	0.00	0.00
6401607	AGSO 05	SM005	s225	13°18.5818	126°02.160	-13.305818	126.034933	0.22	65.00	5y 6 2	90.40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6401608	AGSO 06	SM006	s225	13°24.7508	126°00.421	-13.407508	126.004210	0.05	90.00	2.5 6 4	26.40		32.56	65.53	1.91	15.00	40.00	45.00	0.00	60.00	40.00
6401609	AGSO 07	SM007	s225	13°22.3055	125°42.60	-13.369722	125.706000	0.34	67.50	5y 5 2	122.00		11.93	54.27	33.79	15.00	60.00	25.00	0.00	25.00	75.00
6401610	AGSO 08	SM008	s225	13°25.088	125°29.62	-13.417547	125.489533	0.16	82.50	5y 5 2	65.50		4.66	77.00	18.35	75.00	15.00	10.00	0.00	40.00	60.00
6401611	AGSO 09	SM009	s225	13°22.385	125°24.24	-13.370517	125.402400	0.25	75.00	5y 5 2	92.00		3.90	80.82	15.28	35.00	35.00	30.00	1.00	37.00	57.00
6401612	AGSO 10	SM010	s225	13°25.0068	125°21.027	-13.416735	125.350270	0.15	85.00	5y 6 2	88.80		0.00	0.00	0.00	0.00	30.00	70.00	0.00	20.00	80.00
6401613	AGSO 11	SM011	s225	13°25.0088	125°20.985	-13.416755	125.343183	0.16	82.50	5y 6 2	88.80		31.43	58.13	10.45	10.00	55.00	35.00	10.00	35.00	55.00
6401614	AGSO 12	SM012	s225	13°24.9148	125°12.395	-13.409148	125.203950	0.18	80.00	5y 5 2	82.40		9.63	68.01	22.36	7.00	18.00	75.00	5.00	53.00	47.00
6401615	AGSO 13	SM013	s225	13°24.958	125°09.73	-13.409580	125.157300	0.20	80.00	5y 5 3	82.80		9.72	65.96	24.32	5.00	55.00	40.00	5.00	20.00	75.00
6401616	AGSO 14	SM014	s225	13°21.756	125°06.285	-13.357560	125.102850	0.17	85.00	5y 5 2	76.80		12.18	62.40	25.42	0.00	48.00	52.00	0.00	25.00	75.00
6401617	AGSO 15	SM015	s225	13°25.188	125°06.115	-13.418547	125.101150	0.16	82.50	5y 5 2	78.80		14.69	61.07	24.23	5.00	7.00	88.00	2.00	25.00	73.00
6401618	AGSO 16	SM016	s225	13°30.045	125°10.018	-13.500450	125.166847	0.14	85.00	5y 5 2	81.60		17.30	66.25	16.45	0.00	45.00	55.00	0.00	18.00	82.00
6401619	AGSO 17	SM017	s225	13°33.262	125°13.488	-13.552620	125.221547	0.17	82.50	5y 5 2	78.80		11.58	67.44	20.98	0.00	40.00	60.00	5.00	20.00	75.00
6401620	AGSO 18	SM018	s225	13°35.70	125°15.54	-13.590333	125.255400	0.20	82.50	5y 4 2	67.20		15.08	67.90	17.03	0.00	10.00	90.00	5.00	34.00	61.00
6401621	AGSO 19	SM019	s225	13°33.517	125°06.541	-13.555170	125.105410	0.11	90.00	5y 6 2	72.00		8.69	70.13	21.19	0.00	35.00	65.00	5.00	40.00	45.00
6401622	AGSO 20	SM020	s225	13°30.142	125°06.349	-13.501420	125.103490	0.11	90.00	5y 5 2	72.00		4.37	89.84	5.79	0.00	50.00	50.00	0.00	55.00	45.00
6401623	AGSO 21	SM021	s225	13°29.780	125°02.148	-13.491133	125.034813	0.24	77.50	5y 5 2	100.00		6.52	65.74	27.74	0.00	50.00	50.00	5.00	10.00	85.00
6401624	AGSO 22	SM022	s225	13°27.742	124°59.733	-13.457420	124.990663	0.28	75.00	5y 5 2	104.40		6.56	60.77	32.67	25.00	65.00	10.00	5.00	40.00	55.00
6401625	AGSO 23	SM023	s225	13°25.496	124°57.565	-13.421627	124.955650	0.23	70.00	5y 5 2	105.60		11.20	62.13	26.67	30.00	45.00	25.00	10.00	45.00	45.00
6401627	AGSO 25	SM025	s225	13°25.58	124°5.65	-13.422467	124.089833	0.30	82.50	5y 5 2	117.60		8.82	53.22	37.96	10.00	40.00	50.00	0.00	35.00	65.00
6401628	AGSO 26	SM026	s225	13°25.734	124°47.508	-13.424007	124.788413	0.29	82.50	5y 5 3	102.00		12.14	45.54	42.31	20.00	20.00	60.00	10.00	30.00	60.00
6401629	AGSO 27A	SM027	s225	13°16.86	124°47.63	-13.275267	124.789633	0.60	67.50	5y 5 3	130.00		0.40	7.87	91.74	20.00	60.00	20.00	0.00	0.00	0.00
6401631	AGSO 28A	SM028	s225	13°12.93	124°42.54	-13.209300	124.705400	0.65	67.50	5y 5 3	140.40		0.36	21.42	78.22	30.00	60.00	20.00	0.00	0.00	0.00
6401633	AGSO 29A	SM029	s225	13°17.41	124°38.13	-13.287433	124.634633	0.47	75.00	5y 5 2	133.20		0.32	41.88	57.80	20.00	65.00	15.00	0.00	50.00	50.00
6401635	AGSO 30A	SM030	s225	13°02.19	124°10.77	-13.035233	124.174367	0.15	75.00	5y 4 1	202.40		1.40	93.74	4.86	15.00	30.00	55.00	0.00	0.00	100.00
6401637	AGSO 31	SM031	s225	13°05.769	124°14.906	-13.041023	124.242393	0.32	82.50	5y 6 3	191.20		0.93	71.74	27.33	20.00	75.00	5.00	0.00	0.00	0.00
6401639	AGSO 32	SM032	s225	13°10.281	124°20.462	-13.169477	124.337953	0.17	90.00	5y 6 2	182.00		2.59	89.98	7.43	10.00	75.00	15.00	0.00	35.00	65.00
6401641	AGSO 33	SM033	s225	13°14.795	124°25.919	-13.241283	124.425857	0.27	82.50	5y 6 3	150.80		2.82	74.95	22.24	25.00	35.00	40.00	0.00	30.00	70.00
6401642	AGSO 34	SM034	s225	13°10.12	124°30.04	-13.167867	124.500400	0.41	85.00	5y 5 2	158.80		1.51	67.45	31.05	20.00	60.00	20.00	0.00	30.00	70.00
6401643	AGSO 35	SM035	s225	13°04.829	124°25.861	-13.074957	124.425277	0.32	82.50	5y 5 2	182.00		0.57	71.91	27.51	15.00	75.00	10.00	0.00	25.00	75.00
6401644	AGSO 36	SM036	s225	12°59.383	124°20.209	-13.987163	124.335423	0.24	85.00	5y 5 2	187.90		0.04	88.22	11.74	15.00	80.00	5.00	0.00	0.00	0.00
6401645	AGSO 37	SM037	s225	12°55.98	124°15.99	-13.926467	124.259900	0.27	62.50	5y 5 1	192.40		2.15	80.41	17.43	15.00	70.00	15.00	0.00	35.00	65.00
6401646	AGSO 38A	SM038	s225	13°08.09	124°05.88	-13.134233	124.092133	0.32	62.50	5y 7 1	205.60		0.61	7.13	92.27	10.00	50.00	40.00	5.00	35.00	60.00
6401648	AGSO 39	SM039	s225	13°11.632	124°10.117	-13.189653	124.167837	0.09	92.50	5y 6 2	172.40		9.69	86.49	3.81	0.00	0.00	0.00	0.00	0.00	0.00
6401649	AGSO 40A	SM040	s225	13°15.601	124°14.518	-13.256010	124.238513	0.12	87.50	5y 6 2	152.80		19.72	73.85	6.43	10.00	20.00	70.00	5.00	5.00	90.00
6401653	AGSO 42A	SM042	s225	13°24.998	124°31.54	-13.409980	124.522067	0.33	75.00	5y 5 2	143.60		2.13	52.92	44.95	15.00	60.00	25.00	0.00	0.00	0.00
6401656	AGSO 44A	SM043	s225	13°45.760	124°51.186	-13.757600	124.851860	0.17	87.50	5y 6 2	66.00		6.41	83.95	9.64	20.00	20.00	60.00	30.00	70.00	0.00
6401660	AGSO 46	SM044	s225	13°45.83	124°15.24	-13.758300	124.252400	0.12	87.50	5y 6 2	66.00		12.69	68.79	18.52	0.00	35.00	65.00	0.00	45.00	55.00
6401663	AGSO 48B	SM045	s225	13°52.265	124°55.782	-13.869317	124.924487	0.17	82.50	5y 6 3	66.50		16.35	57.02	26.63	0.00	40.00	60.00	5.00	80.00	15.00

Sample No	Sample	Aquisition method	Survey	South	East	Latitude	Longitude	Total Organic Carbon	CaCO3	Colour	Water Depth	Core Depth	Gravel	Sand	Mud	Fresh Sand	Inter-mediate Sand	Relic sand	Fresh Gravel	Inter-mediate Gravel	Relict Gravel
6401676	AGSO 27B	GC001	s225	13 16 81	124 47 65	-13.274767	124.789833	0.51	68.00	varies	130.00	0.0m	0.80	11.56	87.65	0.00	0.00	0.00	0.00	0.00	0.00
6401677	AGSO 27B	GC001	s225	13 16 81	124 47 65	-13.274767	124.789833	1.50	75.00	varies	130.00	1.0m	0.56	14.51	84.93	45.00	50.00	5.00	0.00	0.00	0.00
6401678	AGSO 27B	GC001	s225	13 16 81	124 47 65	-13.274767	124.789833	0.44	82.00	varies	130.00	1.75m	0.36	17.92	81.73	30.00	60.00	10.00	0.00	0.00	0.00
6401666	AGSO 28B	GC002	s225	13 12 82	124 42 54	-13.208200	124.705400	0.46	74.00	varies	140.00	0.0m	2.98	33.91	63.11	0.00	0.00	0.00	0.00	0.00	0.00
6401667	AGSO 28B	GC002	s225	13 12 82	124 42 54	-13.208200	124.705400	0.31	87.00	varies	140.00	0.85m	5.97	46.53	47.50	30.00	50.00	20.00	0.00	0.00	0.00
6401668	AGSO 28B	GC002	s225	13 12 82	124 42 54	-13.208200	124.705400	0.28	94.00	varies	140.00	1.5m	7.70	30.06	62.24	25.00	6.00	15.00	0.00	0.00	0.00
6401669	AGSO 28B	GC002	s225	13 12 82	124 42 54	-13.208200	124.705400	0.24	92.00	varies	140.00	1.8m	13.98	36.79	49.24	20.00	60.00	20.00	0.00	95.00	5.00
6401679	AGSO 29B	GC003	s225	13 17 32	124 38 21	-13.286533	124.635433	0.44	75.00	varies	133.00	0.0m	0.30	36.55	63.15	0.00	0.00	0.00	0.00	0.00	0.00
6401680	AGSO 29B	GC003	s225	13 17 32	124 38 21	-13.286533	124.635433	0.31	81.00	varies	133.00	0.8m	0.07	39.60	60.33	30.00	65.00	5.00	0.00	0.00	0.00
6401681	AGSO 29B	GC003	s225	13 17 32	124 38 21	-13.286533	124.635433	0.24	90.00	varies	133.00	1.8m	0.13	56.41	43.46	30.00	65.00	5.00	0.00	0.00	0.00
6401682	AGSO 30B	GC004	s225	13 02 154	124 10 689	-13.034873	124.173557	0.19	82.00	varies	202.00	0.0m	1.26	87.66	11.09	0.00	0.00	0.00	0.00	0.00	0.00
6401683	AGSO 30B	GC004	s225	13 02 154	124 10 689	-13.034873	124.173557	0.13	84.00	varies	202.00	0.58m	3.47	73.21	23.32	0.00	0.00	0.00	0.00	0.00	0.00
6401684	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.32	83.00	varies	191.00	0.0m	1.21	73.48	25.31	30.00	50.00	20.00	0.00	75.00	25.00
6401685	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.40	90.00	varies	191.00	0.7m	1.43	34.56	64.01	30.00	50.00	20.00	0.00	50.00	50.00
6401686	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.30	89.00	varies	191.00	1.55m	1.04	40.03	58.93	25.00	30.00	45.00	0.00	0.00	100.00
6401687	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.30	86.00	varies	191.00	1.7m	1.16	29.80	69.04	10.00	55.00	35.00	0.00	20.00	80.00
6401688	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.35	89.00	varies	191.00	2.52m	4.21	51.38	44.40	15.00	45.00	35.00	15.00	15.00	70.00
6401689	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.33	83.00	varies	191.00	3.05m	1.75	42.93	55.31	20.00	60.00	20.00	10.00	40.00	50.00
6401690	AGSO 31B	GC005	s225	13 05 59	124 14 685	-13.089233	124.240183	0.31	84.00	varies	191.00	3.6m	2.39	58.01	39.60	15.00	45.00	40.00	0.00	40.00	60.00
6401691	AGSO 31B	GC005	s225	14 05 59	125 14 685	-14.089233	125.240183	0.23	88.00	varies	191.00	4.57m	4.00	49.02	46.98	25.00	55.00	20.00	0.00	0.00	0.00
6401672	AGSO 38B	GC007	s225	13 07 98	124 05 98	-13.126467	124.093133	0.30	90.00	varies	205.00	0.1m	2.54	17.22	80.24	0.00	0.00	0.00	0.00	0.00	0.00
6401673	AGSO 38B	GC007	s225	13 07 98	124 05 98	-13.126467	124.093133	0.36	90.00	varies	205.00	0.4m	0.22	14.89	84.89	40.00	45.00	15.00	0.00	0.00	0.00
6401674	AGSO 38B	GC007	s225	13 07 98	124 05 98	-13.126467	124.093133	0.40	84.00	varies	205.00	1.05m	2.23	35.58	62.19	20.00	35.00	45.00	0.00	20.00	80.00
6401675	AGSO 38B	GC007	s225	13 07 98	124 05 98	-13.126467	124.093133	0.22	84.00	varies	205.00	2.1m	7.22	62.50	30.28	20.00	30.00	50.00	0.00	0.00	0.00
6401670	AGSO 40B	GC008	s225	13 15 639	124 14 499	-13.256390	124.238323	0.13	94.00	varies	157.00	0.0m	21.81	62.66	15.53	0.00	0.00	0.00	0.00	0.00	0.00
6401671	AGSO 40B	GC008	s225	14 15 639	125 14 499	-14.256390	125.238323	0.23	93.00	varies	157.00	0.85m	0.30	2.99	96.71	30.00	55.00	15.00	0.00		100.00
6401692	AGSO 42B	GC010	s225	13 24 968	124 31 44	-13.409680	124.521067	0.31	81.00	varies	117.00	0.0m	1.67	57.43	40.89	0.00	0.00	0.00	0.00	0.00	0.00
6401693	AGSO 42B	GC010	s225	14 24 968	125 31 44	-14.409680	125.521067	0.33	84.00	varies	117.00	0.9m	0.00	16.80	83.20	20.00	80.00	0.00	0.00	0.00	0.00
6401694	AGSO 42B	GC010	s225	15 24 968	126 31 44	-15.409680	126.521067	0.36	84.00	varies	117.00	1.9m	0.00	11.20	88.80	60.00	40.00	0.00	0.00	0.00	0.00
6401695	AGSO 42B	GC010	s225	16 24 968	127 31 44	-16.409680	127.521067	0.41	83.00	varies	117.00	2.9m	0.27	9.83	89.90	25.00	70.00	5.00	0.00	0.00	0.00
6401664	AGSO 48	GC015	s225	13 52 265	124 55 782	-13.869317	124.924487	0.16	83.00	varies	64.00	0.0m	9.83	66.76	23.41	0.00	0.00	0.00	0.00	0.00	0.00
6401665	AGSO 48	GC015	s225	13 52 265	124 55 782	-13.869317	124.924487	0.10	87.00	varies	64.00	0.85m	41.44	32.84	25.72	20.00	55.00	25.00	0.00	0.00	0.00
6401702	AGSO 48	GC015	s225	13 52 265	124 55 782	-13.869317	124.924487	0.09	88.00	varies	64.00	0.3m	14.70	50.38	34.93	10.00	70.00	20.00	0.00	30.00	70.00
6775	9	SM	anu	-12.591667	123.531667	-12.591667	123.531667		88.00				9.42	75.36	15.22	0.00					
6776	10	SM	anu	-12.500012	123.9	-12.500012	123.900000		97.00				13.35	86.29	0.36	20.00	55.00	25.00	0.00	0.00	0.00
6777	11a2	SM	anu	-12.716668	124.316678	-12.716668	124.316678		94.00				7.46	91.47	1.07	30.00	35.00	35.00	0.00	0.00	0.00
6778	11b	SM	anu	-12.713	124.356167	-12.713000	124.356167		98.00				11.88	82.01	6.11	20.00	40.00	40.00	0.00	0.00	0.00
6779	11c	SM	anu	-12.715	124.347	-12.715000	124.347000		99.00				23.94	70.95	5.11	15.00	20.00	65.00	0.00	0.00	0.00
6780	12a	SM	anu	-12.912167	124.505333	-12.912167	124.505333		99.00				16.59	73.33	10.08	30.00	20.00	50.00	0.00	0.00	0.00
6781	12b	SM	anu	-12.9165	124.500013	-12.916500	124.500013		98.00				22.63	73.83	3.54	15.00	15.00	70.00	0.00	0.00	0.00
6782	12c	SM	anu	12 54 96	124 28 89	-12.909600	124.476267		95.00				22.92	73.94	3.14	30.00	45.00	25.00	0.00	0.00	0.00
6783	14	SM	anu	-13.276167	124.011667	-13.276167	124.011667		94.00				0.00	89.73	10.27	45.00	50.00	5.00	0.00	0.00	0.00
6784	15	SM	anu	-12.915	122.704333	-12.915000	122.704333		96.00				5.71	92.23	2.06	40.00	45.00	15.00	0.00	0.00	0.00
6785	16	SM	anu	-12.191833	123.2945	-12.191833	123.294500		98.00				41.13	58.56	0.31	20.00	30.00	50.00	0.00	0.00	0.00
6786	22	SM	anu	-11.999833	123.691833	-11.999833	123.691833		99.00				6.16	92.33	1.51	0.00	55.00	45.00	0.00	0.00	0.00
6787	23	SM	anu	-12.241667	123.548667	-12.241667	123.548667		99.00				5.13	91.98	2.89	20.00	45.00	35.00	0.00	0.00	0.00
6788	24	SM	anu	-12.2855	123.52	-12.285500	123.520000		94.00				3.57	90.01	6.42	25.00	30.00	45.00	0.00	0.00	0.00
6789	25	SM	anu	-12.331167	123.499667	-12.331167	123.499667		94.00				0.00	98.34	1.66	45.00	55.00	0.00	0.00	0.00	0.00
6790	27	SM	anu	-13.561667	122.014	-13.561667	122.014000		93.00				0.00	99.37	0.63	30.00	30.00	40.00	0.00	0.00	0.00
6793	#9	SM	anu	12 60 708	123 38 039	-13.007080	123.633723		94.00				0.42	97.61	1.97	50.00	35.00	15.00	0.00	0.00	0.00
6794	x	SM	anu	12 04 856	126 06 817	-12.075227	126.108170		80.00				0.68	75.97	23.35	5.00	10.00	85.00	0.00	0.00	0.00
6795	z	SM	anu	12 15 448	123 06 840	-12.254480	123.108400		100.00				15.68	83.52	0.79	40.00	40.00	20.00	0.00	0.00	0.00

Penguin Deep Station No.
Survey Sample Number
AGSO Laboratory Number

Water Depth
Macroscopic Sample Colour

Size Fraction wt %
Photograph
Colour

fresh	interm	relict	wt.% *	Particle type	Comments
				pelecypods	
				gastropods	
				bryozoa	
				benthic forams	
				plank. forams	
				porifera	
				echinoids	
				brachiopods	
				corals	
				serpulids	
				arthropods	
				coralline algae	
				ostracods	
				other bioclasts	
				intraclasts	
				Bio/Intraclast Subtotal	
				phosphate	
				glauconite	
				quartz	
				feldspar	
				lithics	
				other terrig.	
				Total	

ABBREVIATION KEY

Bioclast preservation

a	abrasion
b	bioerosion
de	devitrification
dis	disarticulation
en	encrusted
ex	exfoliation
fr	fragmentation
st	staining
vit	vitreous
aggl	agglutinated
art	articulated
gl	glauconitic infill of internal pores

Particle features

vc	very coarse sand
c	coarse sand
m	medium sand
f	fine sand
vf	very fine sand
rndd	rounded
ang	angular
pol	polished
por	porous μ por microporous

() minor feature ____ dominant feature

* Abundance as Wt % was estimated visually

Bryozoan Forms: M membraniferiform; A adeoniform; V vinculariiform; R reteporiform; L lunulitiform;
C cellariiform/catenicelliform (from Wass, Conolly, & Macintyre, 1970)

Interpretation of relict sediment component

Comments

Appendix 3.3

Sample No	lat	lon	Ship board description	Observations of larger clasts	Microscope observations, a = abraision, b= bioerosion, de = devitrification, dis = disarticulation, en = encrusted, fr =fragment, st =staining, vit =viterous, aggl = agglutinated, art = articulated, gl = glaucontie infill	Other observations
6401603	-13.38446	126.45671	Grey muddy Qtz sand, Glauconitic (10%), minor skeletal fragments (10-20%). Qtz grains poorly rounded, moderately sorted, fine sand size with a muddy component. Glauconite grains are fine grained, dark green and pelloidal. Carbonate grains predominantly platy	Biota : 1 large coral clast 10cm in diameter, 1 crab (unidentified), thin wall pelecypods, gastropods.	the qtz % has been covered with Ca Co3 all grains sub angular to angular all qtz grains fine sand . Relict reworked with no fresh / modern clasts.	
6401604	-13.39000	126.30887	Grey sandy mud, fine sand size Qtz grains (5%), medium to coarse grained angular carbonate grains (20%), dark glauconitic pelloidal aggregates (10%). Small black lithoclasts noted containing fine Qtz and a dark cement.	Biota : Peronella, thin wall bivalves, pectins, coral fragments and various gastropods.	heavily reworked and stained sub angular / rounded. No sed undamaged except pteropod shells, fragments of larger bivalves and some grains with glauconite infilling.	
6401605	-13.20532	126.05580	Creamy brown sand, medium to coarse grained, well sorted, angular carbonate grains (50%), brown stained carbonate lithoclasts (50%), fresh skeletal grains predominantly mollusc and bryozoan fragments.	Biota: Bryozoans associated with sponges.	reworked biogenic sediments	
6401606	-13.30531	126.03613	Minimal recovery, hard substrate, 1 sample bag taken.	Biota: 1 sponge and bryozoan.	indicative of hard substrate with large sponge with pseudopodia, in life position, surpulid worms gastropods echinoderm spines all bioclasts being relict or intermediate in age.	
6401607	-13.30582	126.03493	Minimal recovery indicative of a hard substrate, 1 sample bag taken – teaspoon of sediment.			
6401608	-13.40751	126.00421	Creamy brown sand, coarse grained, moderately sorted, white angular carbonate grains (40%) with brown lithoclasts dominantlv (60%).		all reworked large biogenic material relict is stained and encrusted / crust?	
6401609	-13.36972	125.70600	Light grey muddy sand, fine grained, angular skeletal grains, glauconitic peloids (15%), poorly sorted, contained within a muddy fraction.	Biota: Echinoderms, bivalves, gastropods, lots of solitary corals, pectens, bryozoan fragments. Taken out/one echinoid plate and 3 echinoid spines.	relict very stained, corals are solitary	
6401610	-13.41755	125.48953	Grey muddy sand, abundant angular skeletal debris includes small pelecypods and various skeletal rods, common glauconite (5%), abundant miliolids (benthic forams), minor brown stained carbonate grains.	Biota: Gastropods, solitary corals, echinoderm spines and tests, several different bryozoans, crab shell, agglutinated worm tube, miliolid forams and pelecypods.	solitary corals. Pelecypods, gastropods, bryozoa, echinoderms	
6401611	-13.37052	125.40240	Grey muddy sand, medium grained, angular skeletal debris with a muddy percentage, poorly sorted, brown stained carbonate grains (30%), glauconite (5%), rare miliolid forams.	No coarse fraction.	transported shelfal sed, all rounded and abraided, only one fresh pteropod perhaps bi modal as some much more stained	large bioclasts coloured bryos (pink) st on clasts, relict gastropods bryo serpulids coral frags, a,b,fr,en
6401612	-13.41673	125.35027	Poor recovery, little sediment acquired.		a, b, dis, fr, st, vrd, ang, relict very stained (orange)	a,b,fr,bryo gastro, bivalve bioclasts many pteropod stems.
6401613	-13.41675	125.34318	Little recovery, grey muddy sand, poorly sorted, medium to coarse grained, angular abundant skeletal debris, brown stained lithoclasts common (10%), rare quartz in clasts. miliolids abundant.	Biota: Large cemented clast possibly bryozoan.	a, b, dis, fr, st,	.5 - 2.5 cm pteropods bialves echinodermfr, bryo
6401614	-13.40915	125.20395	Grey muddy very fine sand, glauconite peloids (10%), occasional 1-2mm skeletal clasts, poorly sorted, abundant fine angular skeletal debris.	Biota: Solitary corals, pteropods, bryozoans (vagrant and fenestrate), echinoderm spines, gastropods (broken).	heavily reworked sed, a, broken en, in both interim and relict	bryo, pelecypod, benthic f, gastro pteropods. a,b,fr
6401615	-13.40958	125.15730	Grey muddy fine sand, glauconite peloids (5%), angular skeletal debris common, benthic forams common, small pelecypods, echinoid spines rare as skeletal clasts (5%).	Biota: Pelecypods, gastropods, bryozoans (vagrant and fenestrate), ornate encrusted echinoderm spines, carbonate clasts and pteropods.	many surfaces of the bioclasts are encrusted with bryozoa, a, b, en, dis, fr, st, transported relict material one large bivalve (4c,) not in included in the %'s	large no of individual serpulid tubes, sample dominated by 3 bioclasts > 3cm. No recent material
6401616	-13.35756	125.10285	Grey fine to medium grained muddy sand, angular skeletal grains, benthic forams, trace pelloidal glauconite, 1 bryozoan and pelecypod fragments.	Biota: Solitary corals, bryozoans (vagrant and fenestrate), pelecypods, scaphopod, ornate echinoderm spines.	reworked fr, broken, biogenic sed, 80% same size sediments	50% of the entire sample high in relict gravels w some gastropods, bivalves
6401617	-13.41855	125.10115	Grey fine muddy sand, angular skeletal fragments, glauconitic peloids (2-5%), no real identifiable skeletal fragments	Biota: Pteropod, bryozoans (tubular, fenestrate, vagrant), pelecypods, echinoderms, bivalves, gastropods, scaphopod	a, b, dis, en, fr, st, gl, rndd. Sub angular stained broken	minor sample relict bioclasts
6401618	-13.50045	125.16685	Grey medium muddy sand, skeletal fragments (40%), glauconitic peloids (5-10%), echinoid spines, benthic forams	Biota: Bryozoans (fenestrate, vagrant), echinoderms, gastropods, carbonate clasts, bivalves, pteropods, scaphopods	a, b, dis, en, fr, st, gl, angular stained broken	relict bioclasts gl,en, a,b,fr, interim bivalves arthropods pelecypods gastropods angular and subangular
6401619	-13.55262	125.22155	Grey fine muddy sand, glauconite peloids (2%), skel frags, bryozoans, benthic forams	Biota: gastropods, echinoderms, bryozoans (vagrant, fenestrate, tubular), pelecypods	high bryozoa component both vagrant and fenestrate, interim bryozoa growth on older relict sed	pteropod fragments and one relict bioclast
6401620	-13.59033	125.25540	Grey fine muddy sand skel frags, benthic forams, gastropods, bryozoans, echinoids, pelecypods, glauc peloids (2%)	Biota: pelecypods, bryozoans (fenestrate, branching, vagrant), gastropods, echinoids, scaphopods.	well preserved fine structured corals along with relict rounded stained encrusted clasts	ang relict = bryo bioclasts pelecypods vagrant bryo and interim pteropods
6401621	-13.55517	125.10541	Grey fine muddy sand, skel frags, pelecypods, bryozoans, echinoids, glauc peloids (2%).	Biota: bryozoans (vagrant, fenestrate, branching), pelecypods, encrusted echinoids, gastropods.	coralline fine structures still intact= minimal transportation, mixture of fine layered coral frags and older broken bclasts of bivalves and bryozoa	pelecypods, pteropods solitary corals bivalves a,b,fr,en
6401622	-13.50142	125.10349	Grey fine to medium muddy sand, skel frags, gastropods, bryozoans, glauconitic peloids (2%).	Biota: Bryozoans (fenestrate, tubular), pelecypods, gastropods, encrusted echinoids (sand dollar).	a, b, dis, en, fr, st, gl ang. Reworked biogenic sed encrusted pteropods relict.	bioclasts,fr,a,b, ang, en
6401623	-13.49113	125.03481	Grey mud, fine to medium grained, skel frags unidentifiable, glauc peloids (5%).	Biota: Solitary coral, encrusted echinoids, bivalves, pelecypods, gastropods, pteropod, scaphopod, bryozoans (branching, fenestrate, vagrant).	a, b, dei, en, fr, st. high diversity and weight of gravel % pteropods fresh and interim with st, fr	gastro, pelecyp, interim and relict bivalves a,b,fr
6401624	-13.45742	124.99066	Grey fine sand, angular skel frags, bryozoans, glauconitic peloids (1-2%).	Biota: Pelecypods, bivalves, bryozoans (vagrant, fenestrate), gastropods, solitary coral, scaphopod, pteropod.	a, b, en, fr, st, gl, fresh pteropods relict bioclasts have 5% gl	small sample relict, fr,bioclasts, pteropods,bivalves
6401625	-13.42163	124.95565	Grey fine mud, glauc peloids (1-2%), skel frags unidentifiable.	Biota: Solitary coral, echinoids, bivalves, bryozoans, scaphopods, pteropods, gastropods, forams (marginopora).	a, b, dis, en, fr, st,	fresh gastropod bivalve interim bioclasts, small sample
6401627	-13.42247	124.08983	Grey fine sandy mud, angular skel frags, glauc peloids (1-2%), bryozoans, benthic forams.	Biota: Bivalves, gastropods, pteropods. scaphopods, bryozoans, pelecypods, encrusted echinoids.	interim pteropods in good condition. Relict corals are solitary	gastropod b, bivalve a,b dis
6401628	-13.42401	124.78841	Grey fine muddy sand, glauc peloids (1-2%), angular skel frags unidentifiable.	Biota: Solitary coral 3cm across and 2cm in width removed from sample, pteropods, scaphopods, pelecypods, bivalves, echinoids, gastropods, bryozoans (fenestrate, branching, vagrant).	grain size uniform throughout, pteropods well preserved	bioclasts bryo, sol corals pteropods gastro benthic f
6401629	-13.27527	124.78963	Grey very fine mud, some skel frags but unidentifiable.	No coarse fraction.	very small sample one pteropod with pelecypod, gastropod, and echinoderm spine	all transported, a,b,fr,en,ang arthro pelecypod, ptero, bioclasts
6401631	-13.20930	124.70540	Grey mud, very fine grained, compacted, angular skel frags, gastropods, echinoids, glauc peloids (1-2%).	No coarse fraction.	1 estuarine barnacle = 80% of sample and 20% pelecypod	ptero, bryo,bioclasts, ang,a,b,

Sample No	lat	lon	Ship board description	Observations of larger clasts	Microscope observations, a = abraision, b= bioerosion, de = devitrification, dis = disarticulation, en = encrusted, fr =fragment, st =staining, vit =viterous, aggl = agglutinated, art = articulated, gl = glaucontie infill	Other observations
6401633	-13.28743	124.63463	Grey mud, very fine grained, glauc peloids (2-3%), benthic forams (miliolid – whole shells), fine angular skeletal debris.	Biota: pteropods (several types), bivalves, solitary corals, scaphopod, limited bryozoans.	very small sample 80% pteropod remnants	en,a,b,fr
6401635	-13.03523	124.17437	Light grey sand, medium grained, mod sorted, numerous angular and sub-rounded skel debris, common brown stained carbonate clasts (10-15%), rare skel clasts ~1mm.		very small sample 80% pteropod	en,a,b,fr pteropods and bioclats
6401637	-13.04102	124.24239	Grey fine muddy sand, mod-poorly sorted, abundant sub-rounded skel frags, pteropod spines, abundant gastropods, numerous planktic and benthic forams (70/30), glauc peloids (1%).	No coarse fraction.	very small sample 100% pteropod	bryo, pelecypod, benthic f, gastro. a,b,fr,en
6401639	-13.16948	124.33795	Brown/grey medium-coarse grained sand, numerous rounded skel frags, mod sorted, abundant forams (50%), benthic and planktic (40/60), gastropods, rare brown (Fe stained) skel frags.	Biota: 1 20mm echinoderm (sand dollar).	50% pteropods pelecypods, gastropods, serpulids and other bioclats	70% a,b,fr, en,gl gastro bioclst, pelecypods,other serpulid pteropods
6401641	-13.24128	124.42586	Grey muddy sand, medium grained, poorly sorted, abundant angular skel frags, minor skel clasts ~1mm, gastropods, benthic and planktic forams (40/60), minor bryozoans frags, pteropods, minor glauc peloids (<1%).	Biota: Solitary corals, scaphopod, gastropods, bivalves. pteropods.	a, b, fr, en, dis, (st minimal)	fresh = pelecypods, interim pteropods molluscs relict bioclst and gastropods a,b,fr,dis, en,
6401642	-13.16787	124.50040	Grey muddy sand, fine-medium grained, mod sorted, sub-rounded skel debris, rare skel clasts ~1mm, pteropods, gastropods, benthic and planktic forams, minor glauc peloids (1%), dominantly skel frags.	Biota: Solitary coral, bryozoans (fenestrate), pteropod, gastropods.	a, b, dis, en, fr, very clean sample	all grains have damage form transport.. Gravel pelecypods sol corals benthid f. interim pelecypods
6401643	-13.07496	124.42528	Grey muddy sand, medium grained, poorly sorted, sub-angular skel debris, abundant planktic (lesser amount benthic) forams, minor gastropods, echinoid spines, glauc peloids (1%).		clean sample gastropods benthic and planktic Forams, serpulids, and bioclats	bryo, bivalves,benthic f, serpulids pelecypods, fr,a,b,en
6401644	-13.98716	124.33542	Grey fine grained sand, well to moderately sorted, abundant forams (benthic and planktonic ratio 25:75), gastropods, pteropods, unidentified spines, sub-angular skeletal fragments, minor glauconite pellets.		very small sample of pelecypods gastropod and benthic foraminifera	ptero,bioclats, ,a,b, fr, en, relict aggl bioclats
6401645	-13.92647	124.25990	Grey muddy sand, medium grained, planktonic forams, angular skeletal grains, rare glauconite pellets (1%), moderate to poorly sorted.	Biota: Pteropod, bryozoan (vagrant & fenestrate, bivalves, echinoderms, gastropods, scaphopod.	v small sample, remnants of bioclats a b fr en st	none
6401646	-13.13423	124.09213	Grey sandy mud, fine grained, benthic forams present, sub-angular skeletal grains common, glauconite (5%), brown micrite lithoclasts present, benthic planktonic ratio 70:30, moderately sorted. Coarser grains appear to occur in layers		a, b, dis, en, fr, st solitary corals, vagrant bryozoa,	
6401648	-13.18965	124.16784	Grey brown muddy sand, coarse grained, angular skeletal debris, rare skeletal clasts (1-2mm), pteropods, planktonic and benthic forams (60:40), vagrant bryozoan, textuliria foraminifera, minor glauconite peloids(2%), poorly sorted.	Biota: Solitary corals, bivalves, pelecypods, bryozoans (branching, vagrant and fenestrate), gastropods, pteropod, calcified worm tubes (5cm).		v small smaple, benthis f, gastro, bivalve f bioclats a b fr en st
6401649	-13.25601	124.23851	Grey/brown muddy sand, medium to coarse grained, abundant skeletal fragments, calcified worm tubes, bivalves 3-4mm, lithoclasts present (0.8mm), benthic and planktonic forams, glauconite peloids (1%), rare brown stained carbonate grains (10%).	Biota: Pectens, living bivalves, calcified worm tubes, pteropods, solitary corals, scaphopod, bryozoans (fenestrate and vagrant), echinoid and brachiopods.	a, b, dis, en, st many relict clats (20%) have bryozoa encrusting growth	
6401653	-13.40998	124.52207	Light grey very muddy sand, poorly sorted, medium grained, abundant skeletal material with a large muddy component, rare glauconite (2-4%).	Biota: Solitary corals, gastropods & pteropods.		
6401656	-13.75760	124.85186	Shelly hash sand , gastropods coralline bioclats		a, b, dis, en, fr, st solitary corals, 10% of relict bioclats have gl	
6401660	-13.75830	124.25240	biogenic Muddy gravel sand		3 large clats not included are heavily encrusted. Pelecypods, bryo, b forams, echinoderms spines, bioclats.	
6401663	-13.86932	124.92449	Grey muddy sand, coarse grained, poorly sorted, sub-rounded skeletal fragments, minor benthic and planktic forams (50/50), bryozoans (fenestrate), glauconitic peloids (<1%).	Biota: Bivalves, bryozoans (fenestrate, branching, vagrant), pelecypods, echinoid spines and tests, gastropods, 1 pteropod, 1 scaphopod.	range in grain size form 63 microns to 2 cm. Clean sample	