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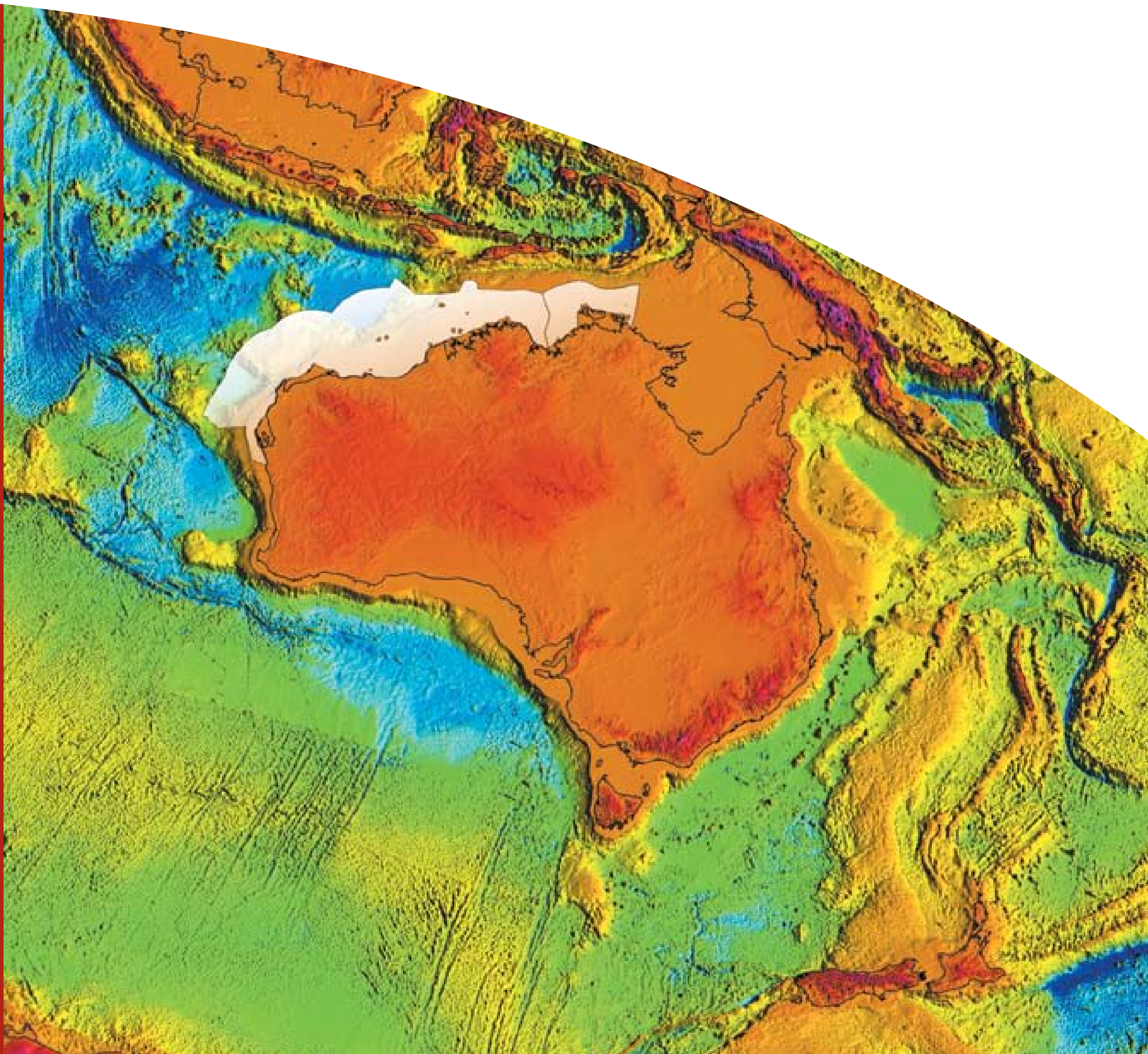
Sedimentology and Geomorphology of the Northwest Marine region

A Spatial Analysis

Christina Baker, Anna Potter, Maggie Tran and Andrew D. Heap

Record

2008/07



APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Geoscience Australia Record 2008/07

Sedimentology and Geomorphology of the North West Marine Region of Australia

Christina Baker, Anna Potter, Maggie Tran and Andrew D. Heap

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Australian Government
Geoscience Australia

Geoscience Australia
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Executive Summary

This report contains a review of literature and the results of a study of the sedimentology and geomorphology of the North West Marine Region (NWMR) and nominated area of the North Marine Region (NNMR). The study is a collaboration between Geoscience Australia and the Department of the Environment, Water, Heritage and the Arts (DEWHA). Data generated by this study expands the national fundamental marine samples dataset for Australia's marine jurisdiction, with analyses consistent with those completed on samples from the rest of the margin. Information contained in this report will contribute to Geoscience Australia's national work program through the creation of seascapes (surrogates for seabed habitats) for the NWMR and will be used by the Department of the Environment, Water, Heritage and the Arts (DEWHA) as part of the Marine Bioregional Planning work program.

Geoscience Australia is the national repository and custodian of marine sediment data including a national marine samples database (MARS; http://www.ga.gov.au/oracle/mars) that is a fundamental marine dataset for the Australian margin. This study has significantly improved the distribution of quantitative textural and composition data stored in MARS for the NWMR and NNMR. To realise the principal aim of the study, the following three objectives were devised:

1. Analyse seabed sediment samples (nominally 200) for quantitative grainsize distribution and carbonate content;
2. Identify sources of marine sediment samples and populate MARS with the data; and
3. Produce a report synthesizing and summarizing the oceanography, tectonic history, late Quaternary evolution, geomorphology and sedimentology of the NWMR and the NNMR based on this data and previous literature.

Results of the analyses are presented as a regional synthesis within the framework of the Integrated Marine and Coastal Regionalisation of Australia (IMCRA) and National Bioregionalisation of Australia 2005 and where possible within the constraints of geomorphic features identified in a recent study of the geomorphology of the Australian margin by Heap and Harris (in press). Reporting the results in this way provides both an updated and quantitative analysis of the regional sedimentology from previous works and characterises the broad-scale management zones designed to support bioregional marine planning. Characterising sedimentology by geomorphic feature allows the resolution of relationships between feature and sediment type.

The NWMR is a tropical carbonate margin that comprises an extensive area of shelf, slope and abyssal plain/deep ocean floor. The northern shelf (Northwest and Sahul Shelves) is broad and gentle with an indiscernible shelf break, and the southern shelf (Dirk Hartog Shelf) is narrow. The northwest margin is controlled by tectonic activity of the Triassic (250 Ma) to Jurassic (145 Ma) that occurred as a result of continental break-up. The margin is influenced by the Leeuwin Current and Indonesian Throughflow, as well as seasonal up-welling events, internal tides and cyclone-induced storms. A series of reefs are located on the outer shelf/slope. Eight bioregions occur within the NWMR, and these include four offshore (~65% of total NWMR area) and four shelf (~35% of total NWMR area) bioregions.

The regional sedimentology is dominated by marine carbonates. Sediments show a broad zoning and fining with water depth. Oceanography, tectonic history, late Quaternary evolution and geomorphology have established the sedimentary setting for the margin. Main sedimentary trends of the NWMR include:

- A tropical carbonate shelf that is dominated by sand and gravel to latitudes of around 15°.
- An outer shelf/slope zone that is dominated by mud; and
- A relatively homogenous rise and abyssal plain/deep ocean floor that is dominated by non-carbonate mud because it occurs below the carbonate compensation depth.

Significant outcomes of this study include:

- Production of the most up-to-date and comprehensive representation of the seabed sedimentology for the northwest and the northern Australian margin, building on existing regional sediment models;
- Production of a detailed synthesis and review of literature for the NWMR and the NNMR;
- Quantification of regional seabed sediment characteristics and distribution in the NWMR and NNMR and assessment of the sediment variability at a NWMR, bioregion and geomorphic feature level;
- Production of a robust, consistent quantitative dataset that permits defensible quantitative comparisons of the seabed sedimentology to be made between the northwest margin and the whole Australian margin; and
- Recognition and quantification of the spatial heterogeneity of seabed sedimentology within the NWMR and the NNMR that can be linked to seabed habitat complexity. Capturing the spatial heterogeneity of the seabed sedimentology will allow more accurate and precise mapping of seabed habitats (seascapes) and aid in more effective future sampling strategies.

A principal application of the study is to support research into the associations between physical seabed properties such as sediment texture and composition and the distribution of benthic marine habitats and biota. This research contributes to Geoscience Australia's work on the spatial representation of benthic marine habitats and biota for Australia's vast marine jurisdiction. This work is crucial for developing robust, defensible methods of mapping habitats over thousands of kilometres using spatially abundant physical data combined with site-specific biological data.

1. Introduction

1.1. BACKGROUND

This report presents the geomorphology and sedimentology of the North West Marine Region (NWMR) and a section of the Northern Marine Region (NMR) termed the nominated area of the (NNMR). The three main outputs of the report include: 1) a review of previous geological research undertaken in the NWMR and NNMR; 2) the results of a quantitative study of seabed sediment texture and composition for these regions; and 3) a synthesis of this information characterising regional trends in sedimentology, geomorphology and bathymetry. The study is a collaboration between Geoscience Australia and the Department of the Environment, Water, Heritage and the Arts (DEWHA) and is a continuation of similar work conducted for the South West Marine Region (Potter et al., 2006; Richardson et al., 2005).

Previous sediment studies in the NWMR have predominantly produced qualitative results at local scales. Existing quantitative textural and compositional data available for the region prior to this task was relatively sparse. The study has improved the coverage of quantitative data for the NWMR by procuring and generating quantitative texture and composition data for 200 nominal seabed samples. This data expands the national marine sediment dataset for Australia's marine jurisdiction, with analyses consistent with those completed on samples from the rest of the margin. By combining results of previous qualitative work and quantitative information generated from existing and new data, this report provides an improved understanding of sedimentology for the NWMR and the NNMR. Information contained within this report will contribute to the Department of the Environment, Water, Heritage and the Arts Marine Bioregional Planning work program and will be one information input used for the selection of candidate marine protected areas for the North West and nominated area of the Northern Marine Region.

Geomorphic, sedimentary and biological information has previously been utilised to develop a National Bioregionalisation of Australia's Exclusive Economic Zone (EEZ) (Department of the Environment and Heritage (National Oceans Office), 2005; now the Department of the Environment, Water, Heritage and the Arts) and substantive geomorphic features of the west, north west and northern continental margins have already been identified and mapped (Heap and Harris, in press). This report adds significantly to these previous studies by incorporating the information in a sedimentological synthesis that includes a discussion of the implications for marine conservation in the NWMR and nominated area of the NMR.

The physical characteristics of the seabed, as described by sediment texture and composition data, can assist in determining the diversity of benthic marine habitats. These data represent "enduring features" which are elements of the physical environment that do not change considerably (in human lifespans), and they are known to influence the diversity of biological systems. This is important for marine conservation due to the better definition and characterisation of benthic habitats. Seabed texture and composition are easily measurable parameters that, when combined with other physical features can be used to create "seascapes" that serve as broad surrogates for benthic habitats and biota (Whiteway et al., 2007). Seascapes have the potential to be used in informing the marine bioregional planning process and the design of a national system of representative Marine Protected Area's (MPA). This data increases the sediment coverage of the NWMR and NNMR to be used in the generation of seascapes.

1.2. SCOPE

1.2.1. Generation and Synthesis of Seabed Information for the NWMR and the NNMR

In April 2007, Geoscience Australia and the DEWHA agreed to undertake a collaborative project to identify, analyse and collate existing information on the texture and composition of the seabed in the NWMR and the NNMR. The main objectives of this project were to:

- Identify and summarise all previous geological information for the NWMR and the NNMR;
- Procure and analyse sediment samples (nominally 200) from the NWMR, currently held by Geoscience Australia and other marine science institutions, for grain size and carbonate concentrations;
- Provide data on the texture and composition of the seabed for the NWMR to populate Geoscience Australia's national marine samples database (MARS; www.ga.gov.au/oracle/mars) with the data; and
- Produce a report synthesising and summarising the sedimentology and geomorphology of the seabed for the NWMR and the NNMR in support of marine bioregional planning and creation of a national system of representative marine protected areas.

1.2.2. Expected Project Outcomes

The expected outcomes of this project are:

- To obtain a better understanding of the nature of the seabed for the west, northwest and northern margins of Australia;
- To improve the available information on the sedimentology of the NWMR for the scientific and planning communities, leading to the development of Marine Bioregional Plans;
- To improve access to data on the nature of the seabed through continued population of the MARS database as a national fundamental marine dataset and
- To provide texture and composition data for future projects; for example, the data may be combined with other physical data on the seabed (i.e. depth, geomorphology, sediment mobility etc) to create 'seascapes' that represent major ecological units based on measurable, recurrent and predictable features of the marine environment.

1.2.3. Products and Outputs

Key outputs of this project will be:

- 200 quantitative textural and compositional data points for the NWMR and associated metadata available in the MARS database;
- A review and synthesis of previous geological information for the NWMR and nominated area of the NMR (Chapter 3);
- Quantitative analyses of the sedimentology and geomorphology of the NWMR and nominated area of the NMR (Chapters 4, 5 and 6);
- A synthesis of all previous and new sediment information for the NWMR and nominated area of the NMR at planning region and bioregion scales (as defined by DEWHA) (Chapters 4, 5 and 6);
- An interpretation of sediment information and discussion of the significant findings and their implications for Marine Bioregional Planning (Chapter 6); and
- A series of web-accessible digital maps to standards appropriate for data coverage and sediment properties in the NWMR and nominated area of the NMR (Appendix G).

1.3. DESCRIPTION OF GEOMORPHOLOGY

In 2004, a collaborative agreement between Geoscience Australia, CSIRO – Marine and Atmospheric Research, and the former Department of the Environment and Heritage (National Oceans Office) created a National Marine Bioregionalisation (NMB 2005) of Australia (Department of Environment, Water, Heritage and the Arts, 2005). The NMB 2005 provides an over-arching management framework for a large part of Australia's marine jurisdiction and is based on the most up-to-date knowledge of the biophysical properties of Australia's marine environment, including seabed geomorphology and sedimentology. Definitions of geomorphic provinces and features included in the NMB 2005 and used in the spatial analyses in this study are listed in Table 2.1.

1.4. MARINE REGIONS

The five marine regions of Australia's Exclusive Economic Zone (EEZ) include the East Marine Region, Northern Marine Region, North West Marine Region and South East Marine Region. Marine bioregional plans will be developed for each of these marine regions including the NWMR outlined in this report.

1.4.1. NWMR and Nominated Area of the NMR

The NWMR encompasses Commonwealth Waters between Kalbarri in Western Australia to the Western Australia and Northern Territory border in the Bonaparte Gulf (Fig. 1.1; Fig.1.2). This region comprises 1.1 million km^2 of ocean and seabed and is bounded inshore by the outer limit of state waters of northern Western Australia (which generally extends out to three nautical miles from the territorial sea baseline), and bounded offshore by the edge of the Australian EEZ (200 nautical miles from the low water mark) except between Cape Leveque and Cape Londonderry, where the NWMR does not extend to the EEZ boundary.

Changes to the location of the marine planning region boundaries have resulted in a portion of the Northern Marine Region (NMR) being excluded from previous geomorphology and sedimentology assessments by Geoscience Australia (Heap and Harris, in press). This area, the nominated area of the Northern Marine Region herein referred to as the NNMR, has been included in the present study. The NNMR covers an area of nearly 200,000 km^2 and includes the seabed and water column from the boundary of the NWMR in the west to the Aurari Bay in the east (Fig 1.1).

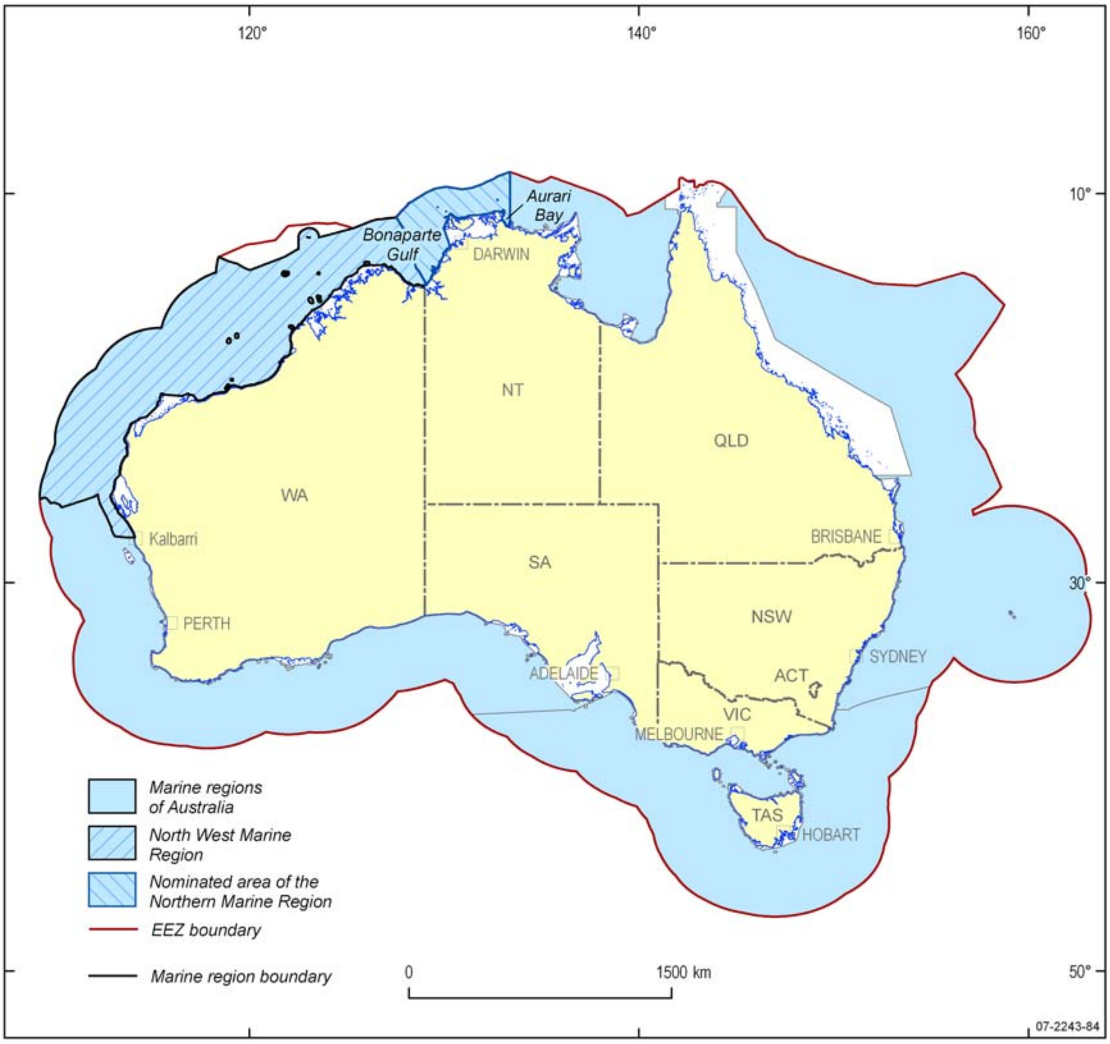


Figure 1.1. Location and extent of the North West Marine Region (NWMR) and nominated area of the North Marine Region (NNMR) relative to other Marine Regions in the Australian EEZ.

1.5. BIOREGIONS

The benthic component of the NMB 2005 management framework consists of a hierarchical set of geographic management units. Below the scale of the major ocean basins that comprise Australia's marine jurisdiction (i.e., the Indian, Southern and Pacific Oceans), the shelf, slope, rise and abyssal plain/deep ocean floor are designated as Primary Bathymetric Units that represent the broadest-scale planning unit and have areas of several million km^2.

Within each of the Primary Bathymetric Units are Provincial Bioregions, which have been defined mainly by the distribution of demersal fish, bathymetry, and geomorphology, and have areas of hundreds of thousands of km² (IMCRA 4.0 2005). The Provincial Bioregions are the principal planning unit for Marine Bioregional Planning. Marine bioregional plans will be developed for each of these marine regions including the NWMR.

1.5.1. Bioregions of the NWMR

The NWMR comprises eight bioregions. (Fig, 1.2 & Table 1.2). Only three of these bioregions are contained entirely within the NNMR boundary. The remainder either occupy areas with water depths <30 m or extend into adjacent marine regions (i.e. the South West Marine Region or NNMR).

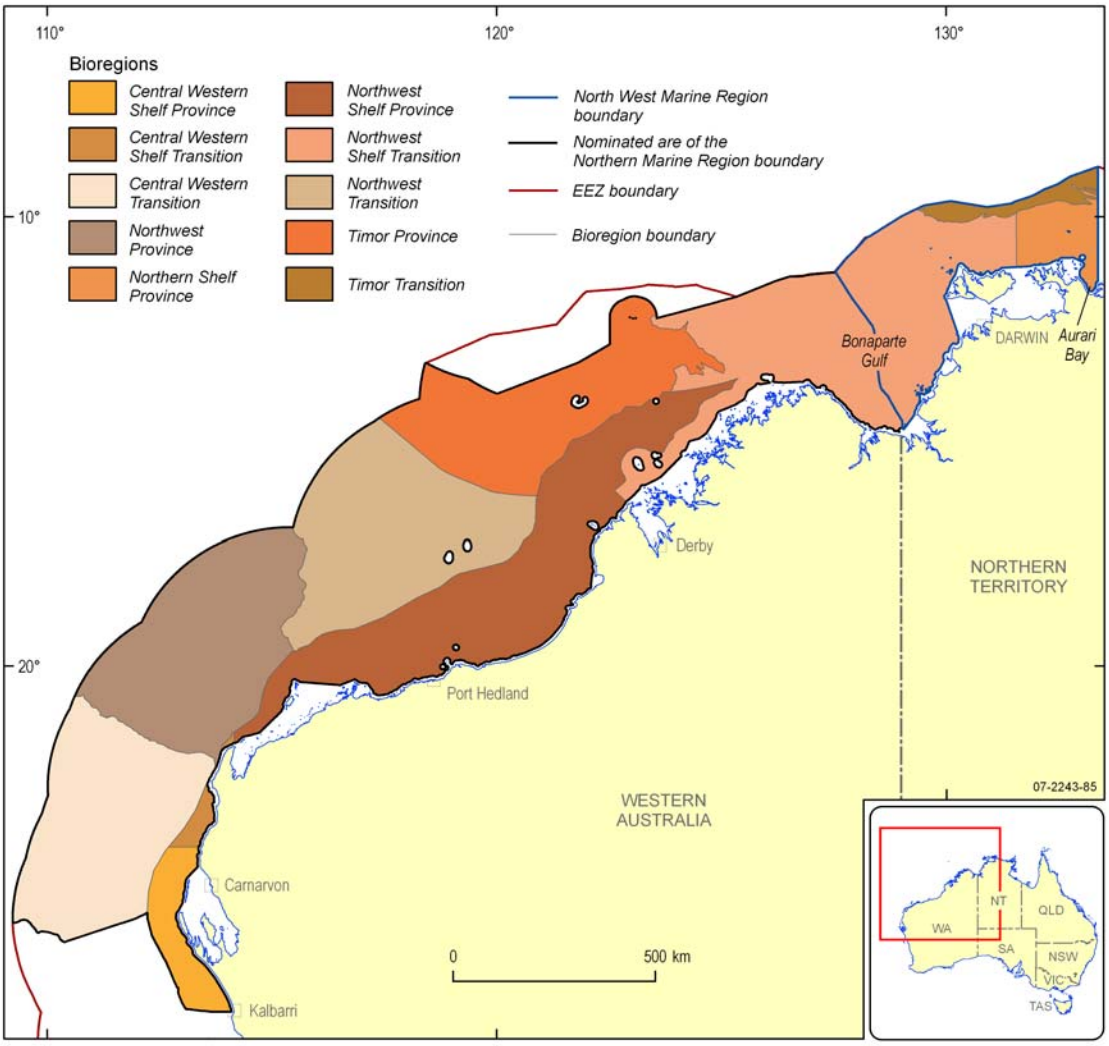


Figure 1.2. Bioregions of the North West Marine Region and nominated area of the Northern Marine Region.

Table 1.2. Summary details of the provincial bioregions contained in the NWMR.

Bioregion	% of bioregion included in NWMR	Water type	% of total NWMR area
Northwest Shelf Transition	44	Transitional Waters	13
Northwest Shelf Province	88	Tropical Waters	20
Central Western Shelf Transition	76	Transitional Waters	1
Central Western Shelf Province	65	Subtropical Waters	3
Central Western Transition	100	Transitional Waters	15
Timor Province	72	Tropical Waters	15
Northwest Transition	100	Transitional Waters	17
Northwest Province	100	Tropical Waters	17

The NWMR contains the Northwest Shelf Province, Central Western Shelf Transition, Central Western Shelf Province, and part of the Northwest Shelf Transition (Table 1.2). These provinces and transitions are located on the shelf. Water depths in the shelf bioregions are between 10 m and 350 m but are generally <150 m.

The NWMR also contains the Timor Province, Northwest Province, Northwest Transition and Central Western Transition (Table 1.2). These provinces and transitions mostly cover the slope and smaller area of the rise and abyssal plain/deep ocean floor. They are bounded by the shelf break, and water depths vary from 150 m to almost 6,000 m.

Full details of the bioregions are presented in Chapter 5. To support regional marine planning in the NWMR, the results of this study are discussed in the context of the provincial bioregions, and data are presented for individual bioregions.

1.5.2. Bioregions of the Nominated Area of the NMR (NNMR)

The NNMR addressed in this report is comprised of three bioregions (Table 1.3; Fig. 1.2). None of these bioregions are contained entirely within the NNMR boundary because they either occupy areas with water depths <30 m or extend into adjacent marine regions (i.e. the NWMR or NMR).

Table 1.3. Summary details of the provincial bioregions contained in the nominated area of the NMR.

Bioregion	% bioregion included in nominated area of NMR	Water type	% total nominated area of NMR area
Northwest Shelf Transition	42	Transition	66
Northern Shelf Province	9	Tropical Waters	25
Timor Transition	74	Transition	9

The nominated area of the NMR contains part of the Northwest Shelf Transition, Northern Shelf Province and the Timor Transition (Table 1.3). Full details of the bioregions are presented in

Chapter 5. As for the NWMR, results of this study are discussed in the context of the Provincial Bioregions, and data are presented for individual bioregions.

The entire area (179,200 km^2) of the two shelf provinces and transitions are located on the shelf. A small area of slope is present in the Timor Transition in the northeast of the nominated area of the NMR.

Water depths in the nominated area of the NMR vary between 10 and 350 m. Deepest areas occur on the slope along the outer boundary of the EEZ. Sample coverage in the nominated area of the NMR is relatively even, with minor data gaps existing locally at several location on the inner shelf and one location on the mid- outer shelf in the west of the region.

1.6. REPORT STRUCTURE

The report provides a regional assessment of the sedimentology and geomorphology of the NWMR and NNMR. The report provides a synthesis of the existing sedimentology and geomorphology of the NWMR and NNMR (Chapter 3) which provides a framework in which the new data can be understood. This is followed by a regional scale spatial analysis of the sedimentology and geomorphology for the NWMR and NNMR (Chapter 4) and for each provincial bioregion occurring in the NWMR (Chapter 5), putting the new data into the context of the planning zones used by DEWHA. Lastly, results of this study and previous work in the NWMR and NNMR are summarised and discussed in terms of their implications for marine planning (Chapter 6).

2. Data and Methods

This chapter outlines the available physical data sets for the NWMR and NNMR and the process of acquiring additional sediment samples to fill gaps in data coverage. Chapters 2.1 – 2.3 provide details of existing quantitative physical data sets for the NWMR and NNMR that have been used in this study. Chapters 2.4 – 2.7 discuss the procedure for identifying (from both internal and external data repositories), selecting and procuring samples, and generating the grainsize and carbonate data. All of the metadata and assays from the procurement and analysis of the samples are contained in Geoscience Australia's marine samples database, MARS.

2.1. EXISTING PHYSICAL DATA FOR THE NWMR

2.1.1. Bathymetry

Bathymetric data for the EEZ and all smaller divisions within it were derived from classifications of the Australian Bathymetry and Topography Grid (June 2005). The grid is a synthesis of 1.7 billion observed data points, and resolution at any point is equal to or better than 250 m. It provides full coverage of Australia's EEZ including areas under Australian jurisdiction surrounding Macquarie Island and the Australian Territories of Norfolk Island, Christmas Island, and Cocos (Keeling) Islands. The area selected does not include Australia's marine jurisdiction off the Territory of Heard and McDonald Islands and the Australian Antarctic Territory.

Water depths for individual data points and ranges for data points were sourced from original survey documentation. Metadata did not include water depths for around 30% of the total data points used in this study. Depths for these points were generated by intersecting point data with the Australian Bathymetry and Topography Grid.

2.1.2. Geomorphology

Geomorphic province and feature boundaries for the EEZ and all smaller divisions within it were derived from a recent study of the geomorphology of Australia's margin and deep seafloor (Heap and Harris, in press). These boundaries were delineated using the 250 m bathymetry grid and previous local seabed studies. Feature names are based on those endorsed by the International Hydrographic Office (IHO 2001). Features are nested within larger geomorphic provinces of shelf, slope, rise and abyssal plain/deep ocean floor (Table 2.1).

Table 2.1. List of geomorphic provinces and features represented in the NWMR and NNMR (Heap and Harris, in press-a). Original definitions are adapted from IHO (2001), except for sand waves and sand banks, which are from Ashley et al. (1990).

No.	Name	Definition
Geomorphic Provinces		
-	Shelf	Zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope

		towards oceanic depths.
-	Slope	Slope seaward from the shelf edge to the upper edge of a continental rise or the point where there is a general reduction in slope.
-	Rise	Gentle slope rising from the oceanic depths towards the foot of a continental slope.
-	Abyssal Plain/ Deep Ocean Floor (AP/DOF)	Extensive, flat, gently sloping or nearly level region at abyssal depths.
Geomorphic Features		
1	Shelf (unassigned)	Area of Shelf Geomorphic Province in which no other geomorphic features have been identified
2	Slope (unassigned)	Area of Slope Geomorphic Province in which no other geomorphic features have been identified
3	Rise (unassigned)	Area of Rise Geomorphic Province in which no other geomorphic features have been identified
4	AP/DOF* (unassigned)	Area of Abyssal Plain/ Deep Ocean Floor Geomorphic Province in which no other geomorphic features have been identified
5	Bank/shoal	Elevation over which the depth of water is relatively shallow but normally sufficient for safe surface navigation. Offshore hazard to surface navigation that is composed of unconsolidated material.
6	Deep/hole/valley	Deep: In oceanography, an obsolete term which was generally restricted to depths greater than 6,000 m. Hole: Local depression, often steep sided, of the sea floor. Valley: Relatively shallow, wide depression, the bottom of which usually has a continuous gradient. This term is generally not used for features that have canyon-like characteristics for a significant portion of their extent.
7	Trench/trough	Trench: Long narrow, characteristically very deep and asymmetrical depression of the sea floor, with relatively steep sides. Trough: Long depression of the sea floor characteristically flat bottomed and steep sided and normally shallower than a trench.
8	Basin	Depression, characteristically in the deep sea floor, more or less equidimensional in plan and of variable extent.
9	Reef	Rock lying at or near the sea surface that may constitute a hazard to surface navigation.
10	Canyon	A relatively narrow, deep depression with steep sides, the bottom of which generally has a continuous slope, developed characteristically on some continental slopes.
11	Knoll/abyssal hills /hill/mountains/peak	Knoll: Relatively small isolated elevation of a rounded shape. Abyssal Hills: Tract, on occasion extensive, of low (100-500 m) elevations on the deep sea floor. Hill: Small isolated elevation. Mountain: Large and complex grouping of ridges and seamounts. Peak: Prominent elevation either pointed or of a very

		limited extent across the summit.
12	Ridge	(a) Long, narrow elevation with steep sides. (b) Long, narrow elevation often separating ocean basins. (c) Linked major mid-oceanic mountain systems of global extent.
13	Seamount	Large isolated elevation, greater than 1000 m in relief above the sea floor, characteristically of conical form
	Guyot	Seamount having a comparatively smooth flat top
14	Pinnacle	High tower or spire-shaped pillar of rock or coral, alone or cresting a summit. It may extend above the surface of the water. It may or may not be a hazard to surface navigation.
15	Plateau	Flat or nearly flat area of considerable extent, dropping off abruptly on one or more sides.
16	Saddle	Broad pass, resembling in shape a riding saddle, in a ridge or between contiguous seamounts.
17	Apron/fan	Apron: Gently dipping featureless surface, underlain primarily by sediment, at the base of any steeper slope.
		Fan: Relatively smooth, fan-like, depositional feature normally sloping away from the outer termination of a canyon or canyon system.
19	Sill	Sea floor barrier of relatively shallow depth restricting water movement between basins.
20	Terrace	Relatively flat horizontal or gently inclined surface, sometimes long and narrow, which is bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.
21	Tidal sandwave/sand bank	Sandwave: Wave-like bed form made of sand on the sea floor.
		Sand bank: Submerged bank of sand in a sea or river that may be exposed at low tide.

2.1.3. Sediment Data

A total of 575 samples in the NWMR and 318 in the NNMR with quantitative sediment data were available in the MARS Database prior to this study. These sample locations contained bulk carbonate, grainsize (Wt%; µm) and/or laser grainsize (Vol%; µm) data. Quantitative carbonate data were available for 550 samples in the NWMR and 264 samples in the NNMR. Quantitative grainsize data were available for 557 samples in the NWMR and 313 samples in the NNMR (Fig. 2.1). The samples were sourced from 20 marine surveys conducted between 1959 and 2006 (Table 2.2), and included dredge, grab and core samples. Samples that occur outside of the NWMR were included to supplement scarce data for the abyssal plain /deep ocean floor to capture the full spectrum of environments.

Where quoted, sediment coverage statistics are calculated from textural data only (mud, sand, and gravel fractions). These also reflect the distribution of carbonate data except in the Central Western Shelf Transition around Shark Bay where there exist 11 additional carbonate assays.

All sample and assay data was quality controlled, and those samples that failed to meet the minimum metadata standards outlined in Geoscience Australia's Data Standards, Validation and Release Handbook, 4th Edition (2004) were excluded from the analysis. Only analyses conducted on dredges, grabs or the top 0.1 m of a core and where the gravel, sand and mud fractions totaled 100% +/- 1% were included. Core samples that did not include depth measurements were also excluded, and duplicates were removed. Ongoing quality control of data may have resulted in slight variations between total samples reported in this document and milestone progress reports.

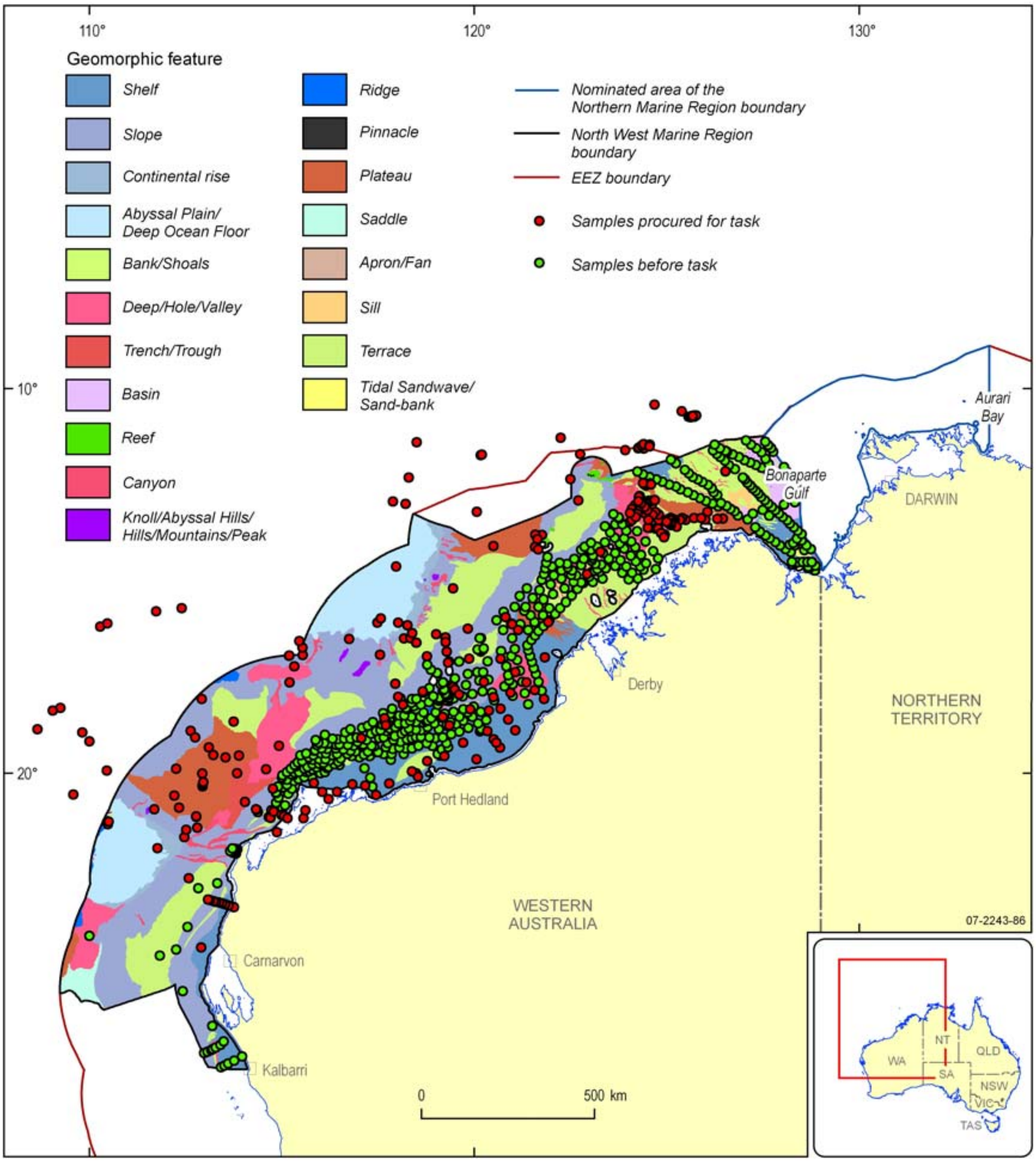


Figure 2.1. Samples with either carbonate and/or grainsize data available in the MARS database prior to and following the task in relation to bioregions of the NWMR and NNMR. See Figure 3.5 for unobstructed view of geomorphic features

Table 2.2. Metadata for sediment samples with either carbonate or grainsize data in MARS for the NWMR prior to the Memorandum Of Understanding (MOU).

Survey Name	Vessel	Year	Sample Types	No. of Samples
ANU/CSIRO				
FR 10/1995	Franklin	1995	Gravity cores	3
CSIRO				
Southern Surveyor 07/2005	Southern Surveyor	2005	Grabs	19
Curtin University				
Holocene Biogenic Sedimentation, Nth Rottnest Shelf.	Franklin	1996	Benthic and pipe dredges	11
DEWHA				
Mermaid Reef	Bhagwan K	2006	Grabs	1
GEOMAR (Germany)				
Sonne 8	Sonne	1979	Box and gravity cores	13
Geoscience Australia				
North West Shelf Sampling 1	Kos II	1967	Grabs	142
North West Shelf Sampling 2	Espirito Santo	1968	Grabs	196
Central North West Shelf Seepage	Southern Surveyor	2006	Grabs, gravity cores and vibro cores	72
Scripps Institute of Oceanography				
Timor Sea 1	Matila	1960	Grabs and gravity cores	49
Timor Sea 2	Stranger	1961	Dredges, grabs and gravity cores	44
University of Sydney				
Holocene Terrigenous Sedimentation, NT	Un-named 15 m+ small boat	1979	Pipe dredges	23
University of WA				
Shark Bay, WA	Un-named 15 m+ small boat	1956	Grabs	2

Table 2.3. Metadata for sediment samples with either carbonate or grainsize data in MARS for the NNMR.

Survey Name	Vessel	Year	Sample Types	No. of Samples
CSIRO				
AUROREX: Part B, Leg 1	Sprightly	1982	Grabs	5
CSIRO Surveys in NT and WA	Un-named 15 m+ small boat	1989	Grabs	12
Geoscience Australia				
Arafura Sea 1	Yamato	1969	Dredges	57
Arafura Sea 2	San Pedro Sound	1969	Dredges	90
Arafura Sea Marine Survey	Southern Surveyor	2005	Grabs and gravity cores	9
Parks and Wildlife, NT				
Beagle Gulf Benthic Survey	Kunnunyah	1993	Dredges	7
Scripps Institute of Oceanography				
Timor Sea 1	Matila	1960	Gravity cores	63
Timor Sea 2	Stranger	1961	Dredges, grabs and gravity cores	66
University of Sydney				
Holocene Terrigenous Sedimentation, NT	Un-named 15 m+ small boat	1979	Pipe dredges	9

2.2. PREVIOUS DATA COVERAGE OF THE NWMR

Prior to this study the majority of samples within the NWMR were recorded from within the Northwest Shelf Province, the Northwest Transition and the Northwest Shelf Transition (Fig. 2.1). A total of 871 of the 894 pre-existing sediment samples occurred in water depths of 10-500 m within the shelf and slope geomorphic provinces. The shelf (unassigned), slope (unassigned) and terrace geomorphic features contained the most samples, while significantly fewer samples occurred on abyssal plain/deep ocean floor (unassigned), apron/fan, canyon, knoll/abyssal hills/hills/mountains/peak, reef, sill, tidal sand waves/sandbanks, and trench/trough geomorphic features.

Highest sample density occurred on the shelf and slope of the Northwest Shelf Province, the Northwest Transition and the Northwest Shelf Transition. In each of these bioregions, most samples occur within 0-0.025 km of the nearest sample.

2.3. ASSESSMENT OF SIGNIFICANT GAPS IN EXISTING SAMPLE COVERAGE FOR THE NWMR

The relationship between data coverage and the other physical variables determines the accuracy of the final interpretations of sediment distribution. The NWMR contains areas where samples, for various reasons, provided insufficient coverage to estimate sediment distribution. Recognition of these gaps was used to guide sample selection for this study. A targeted approach for the addition of sediment data allows for more efficient improvement in sediment information for the NWMR in the short to medium term. Similar assessment of gaps in data coverage resulting from this task (Chapters 4 & 5) will be used to guide sample collection and procurement in the future.

Three types of data gaps were identified and used to guide sample procurement for this study, namely:

- Gaps in spatial coverage. This was determined by mapping data density across the NWMR and identifying areas in the Provincial Bioregions, primary bathymetric units and geomorphic features, where the least samples existed for large areas of seabed.

- Gaps in spatial coverage of specific features. An assessment of distribution of samples within the area of a provincial bioregion, primary bathymetric unit or geomorphic feature, was conducted by assessing the coverage of the number of separate occurrences of the feature and degree to which samples are clustered within these. This determines whether assays are likely to be representative of the range and relative proportion of sediment types.

- Knowledge gaps are not always directly related to sample density. Conceptual understanding of seabed morphology in different geomorphic features and high resolution information derived from local studies and seabed images means that we can estimate the sample spacing required to map actual variations in seabed character to a given resolution. Comparison between this required sample density and the density of existing data can be used to identify areas where data is inadequate to estimate sediment properties.

2.4. SAMPLE IDENTIFICATION IN THE NWMR AND SELECTION FOR ANALYSIS

2.4.1. Sample Identification

MARS database

Prior to this study, a total of 930 samples without grainsize data and 1,800 samples without calcium carbonate data were contained in MARS. More than 1,000 of these were located in Geoscience Australia's archives. The remainder were located in external institutions, including: Federal Institute for Geosciences and Natural Resources (BGR) Germany, Lamont Doherty Earth Observatory and the University of Adelaide, or they were found to no longer exist.

External Databases

A total of 150 samples were also identified in external databases including the National Oceanic and Atmospheric Administration (NOAA) database and the Integrated Ocean Drilling Program core database. 70 were confirmed to contain adequate volumes of surficial sediment to be sub-sampled. These samples were located at six international institutions: Oregon State University, Integrated Ocean Drilling Program Texas A&M University, Research Centre for Marine Geosciences (GEOMAR) Germany, BGR Germany, Scripps Institute of Oceanography and Lamont-Doherty Earth Observatory.

2.4.2. Sample Selection

A total of 297 samples were selected for analysis for this study based on the gap analysis. These consisted of core, dredge and grab samples collected on 25 surveys conducted between 1964 and 2004 (Table 2.4). 163 samples were located in the Geoscience Australia data repository, and 134 were located in external repositories, including: BGR and GEOMAR, Germany; Lamont Doherty Earth Observatory; Oregon State University; Integrated Ocean Drilling Program Texas A&M University; and the University of Adelaide.

Significant data gaps were identified in the Central Western Shelf Transition, Central Western Province, Central Western Transition, Timor Province and Northwest Province. Sediment samples increase coverage of all bioregions except for the Central Western Province. Data coverage of the Central Western Shelf Transition, the Central Western Province and the Central Western Transition remains limited; however, sample density in the Timor and Northwest Provinces is increased.

Significant spatial data gaps were identified especially for deep-water (>4000 m) areas of the NWMR. The addition of 297 samples has significantly increased sample density on the lower slope and abyssal plain/deep ocean floor; however, relative to shallower areas coverage in these areas remains sparse (abyssal plain/deep ocean floor average sample density <1:10,000 km^2, shelf coverage 1: 700 km^2). Few samples have been collected in deepwater areas of the NWMR (>4000 m) that are not now included in our sample coverage. To improve our understanding of sediment distribution in deep-water areas, 42 samples from extensions of these features adjacent to the NWMR were selected for analysis. These points have been used to characterise the sedimentology of the abyssal plain/deep ocean floor and lower slope within the NWMR.

Table 2.4. Metadata for sediment samples analysed for this study.

Survey Name	Vessel	Year	Sample Types	No. of Samples
ANU				
FR 03/1996	Franklin	1996	Gravity cores	15
Curtin University				
Holocene Biogenic Sedimentation, Nth Rottnest	Franklin	1996	Benthic and pipe dredges	10

Shelf.

Deep Sea Drilling Program				
DSDP 27	Glomar Challenger	1972	Core catcher	1
GEOMAR (Germany)				
Sonne 7	Sonne	1978	Grabs and gravity cores	32
Geoscience Australia				
North East Australia Heat Flow	Rig Seismic	1986	Gravity cores	8
Exmouth Plateau 2	Rig Seismic	1986	Gravity cores	1
Canning Exmouth	Rig Seismic	1990	Gravity cores	1
Vulcan Graben 2	Rig Seismic	1990	Grabs and vibro cores	28
Bonaparte 1	Rig Seismic	1991	Vibro cores	2
Sahul Shoals	Rig Seismic	1993	Vibro cores	8
Timor Sea Geology	Rig Seismic	1997	Gravity cores	21
Franklin Cruise 5	Franklin	2000	Grabs and gravity cores	42
Seeps and Signatures 1	Parmelia K	2004	Grabs and gravity cores	27
BGR (Germany)				
Scott Plateau and Java Trench	Valdivia	1977	Piston cores	2
Lamont Doherty Earth Observatory				
Vema Cruise 20, Leg 8	Vema	1964	Piston cores	3
Vema Cruise 24, Leg 9	Vema	1967	Piston cores	1
Conrad Cruise 11, Leg 7	Robert D Conrad	1967	Piston cores	3
Conrad Cruise 14, Leg 3	Robert D Conrad	1971	Piston cores	7
Vema Cruise 28, Leg 11	Vema	1971	Piston cores	8
Vema Cruise 33, Leg 14	Vema	1977	Piston cores	5
Vema Cruise 34, Leg 4	Vema	1977	Piston cores	1
Ocean Drilling Program				
Ocean Drilling Program, Leg 122 & 123	Joides Resolution	1988	Piston cores	7
Oregon State University				
MD 111	Marion Dufresne	1998	Piston cores	2

University of Adelaide				
Franklin Cruise 4	Franklin	1999	Benthic dredges	62

2.5. SAMPLE ACQUISITION AND ANALYSIS

Samples from repositories outside Australia were sent to Geoscience Australia. Material held at Adelaide University by Dr Yvonne Bone was sub-sampled by project officers. Between 12 and 50 g of sediment were used for grainsize and carbonate analyses. Each sample was analysed as follows:

- **Grainsize (Vol%; μm):** The grainsize distribution of the 0.01–2,000 μm fraction of the bulk sediment was determined with a Malvern Mastersizer 2000 laser particle analyser. All samples were wet sieved through a 2,000 μm mesh to remove the coarse fraction. A minimum of 1 g was used for samples comprising relatively fine material and between 2–3 g for samples comprising relatively coarse material. Samples were ultrasonically treated to help disperse the particles. Distributions represent the average of three runs of 30,000 measurement snaps that are divided into 100 particle size bins of equal size.
- **Grainsize (Wt%):** Gravel, sand, and mud concentrations were determined by passing 10–20 g of bulk sediment through standard mesh sizes (Gravel >2,000 μm; Sand 63 μm-2,000 μm; Mud <63 μm). The resulting gravel, sand, and mud concentrations represent dry weight proportions.
- **Carbonate content (Wt%):** Bulk, sand and mud carbonate concentrations were determined on 2–5 g of material using the 'Carbonate bomb' method of Muller and Gastner (1971). Carbonate gravel concentrations were determined by visual inspection.

All analyses were conducted by the Palaeontology and Sedimentology Laboratory at Geoscience Australia. Where sample volumes were insufficient to complete all analyses, laser grainsize and bulk carbonate were completed as a priority. Further information on the data analysis is available in Appendix C.

2.6. ASSESSMENT OF SIGNIFICANT GEOMORPHIC FEATURES

Prior to this study, analysis of sediment type and distribution was completed at Bioregional Planning Region and Bioregion scales. Within these regions, analysis was also completed for features identified as 'significant'. Significant features are defined as single or groups of geomorphic features that characterise the seabed and therefore represent potentially significant areas for conservation that are based on a set of criteria (Table 2.5). Significant features have been identified for the NWMR and individual bioregions within it. Significance of features could not be assessed at international scales as equivalent datasets are not available for areas outside of the AEEZ. Where a feature (significant or otherwise) contained <3 samples, quantitative analysis of sedimentology within this feature was not undertaken due to the low number of samples. Sedimentology for significant features without adequate quantitative data is described from previous studies where possible.

Table 2.5. Criteria for assessing significance of geomorphic features in the NWMR or Provincial Bioregion.

Criteria	Explanation
Feature is best represented in NWMR or Bioregion	Feature covers significant area of the NWMR or bioregion **OR** Feature is not abundant elsewhere in Australia's EEZ (significant portion of total area of this feature occurs in NWMR or bioregion)
Feature is unique to NWMR or Bioregion	This occurrence has a physical attribute i.e: -extent -sedimentology -bathymetry -latitude that differs from that of other occurrences of this feature in the NWMR or EEZ

2.7. MAP PRODUCTION

2.7.1. Percent Gravel/Sand/Mud and Folk Classification and Percent Carbonate

Maps for %Gravel, %Sand, %Mud, Folk Classification, and %Carbonate were clipped from rasters created for the entire EEZ. These were created by:

- Querying the MARS database to obtain all numeric grainsize and carbonate content data for Australia's EEZ and any samples located outside the EEZ but within 100 km of the boundary;
- Compiling the results into gravel, sand and mud fractions (%), mean grainsize (μm) and carbonate (%);
- Checking that gravel, sand and mud for each sample had all three fractions reported, and that these fractions were in the appropriate range when summed (100 +/- 1%); and then
- Resolving cases of duplication.

The sediment classification proposed by Folk (1954) has been used to present information on sediment type. Sediment fraction interpolations were combined into a single raster file and values for each cell at 0.05 decimal degree resolution were exported as points. Folk classes were defined from Folk (1954) diagram and a script automating classification based on these definitions was written in Perl. This script was applied and results exported to point data. Classified cell values were imported back into ArcGIS for map production. Areas for classes on all interpolated maps are calculated only for the interpolated area that lies within the NWMR.

3. Review and Synthesis of Literature for the North West Marine Region

3.1. THE NORTH WEST MARINE REGION

3.1.1. Introduction

The tectonic history, oceanography, late Quaternary evolution and surficial sedimentology of the North West Marine Region (NWMR) have been the focus of extensive research by various authors and government agencies at different temporal and spatial scales. The North West Margin[1] is a tropical carbonate margin and has been since the Eocene (~56 Ma). The NWMR region includes notable geomorphic features and covers an extensive area of shelf, slope and abyssal plain/deep ocean floor. Geoscience Australia has contributed extensively to the study of the region and has published records on the North West Shelf (Exon, 1994; Exon and Colwell, 1994; Jones, 1973), Timor Sea (van Andel and Veevers, 1967), Sahul Shoals (Marshall et al., 1994), Exmouth Plateau (Stagg et al., 2004), Scott Plateau and Rowley Terrace (Ramsay and Exon, 1994; Stagg and Exon, 1981), Carnavorn Terrace (Heggie et al., 1993), Wallaby Plateau (Sayers et al., 2002) and Argo Abyssal Plain (Buffler, 1994). Key geomorphic features and provinces of the NWMR have been mapped using a consistent bathymetric grid of Australia's EEZ (Heap and Harris, in press) and relevant scientific literature.

On the basis of relevant literature, the NWMR is divided into four physiographic regions: the inner shelf; middle shelf; outer shelf/slope; and abyssal plain/deep ocean floor (Fig 3.1). These divisions are made on the basis of water depth and the geomorphic provinces described in a recent study on the geomorphology of the Australian margin (Heap and Harris, in press-b). The inner shelf is between ~ 0-30 m and is characterised by highly turbid water throughout the year. The outer shelf/slope region extends from ~ 200 m water depth to the base of the slope, as defined by Heap and Harris (in press), to where there is a general reduction in gradient to <1:1000 and water depths are >4,000m. The middle shelf is defined as the region between 30 and 200 m water depths. Rise occurs within the NWMR and because of its limited extent, it is not treated here as an exclusive physiographic division. Abyssal plain/deep ocean floor regions are defined as flat or gently sloping regions in abyssal depths greater than ~ 4,000 m (Heap and Harris, in press-b).

[1] 'North West Margin' has been used in petroleum publications to refer to the area of shelf and slope between Exmouth and the Bonaparte Gulf.

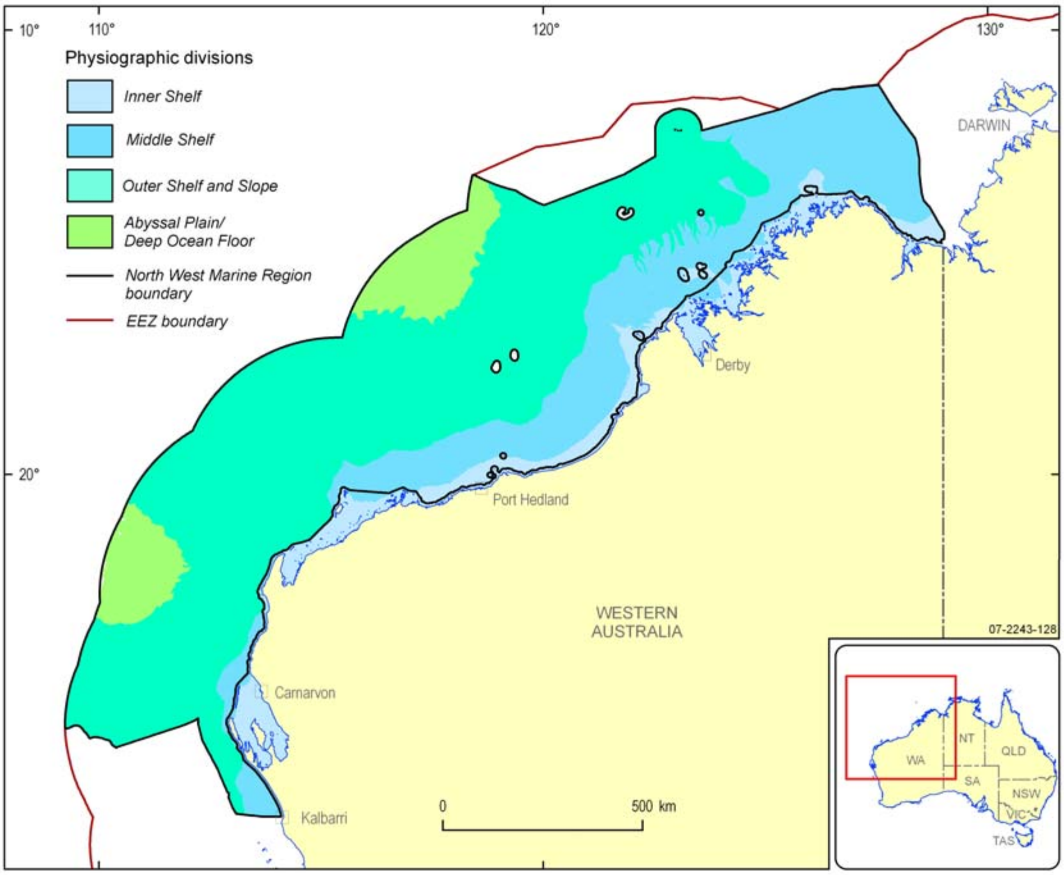


Figure 3.1. Physiographic division of the NWMR, including the inner, middle outer shelf/slope and abyssal plain/deep ocean floor.

3.1.2. Tectonic History

The continental margin of the NWMR has a complex tectonic history characterised by continental break-up, subsidence and deposition, fluvio-deltaic sedimentation, carbonate deposition, siliclastic deposition, thermal uplift and erosion, faulting, and a major period of rift volcanics (Exon and Colwell, 1994). Notable works have been complied by Geoscience Australia (Buffler, 1994; Colwell et al., 1994a; Colwell et al., 1994b; Exon, 1994; Gopala et al., 1994; Ramsay and Exon, 1994; Shafik, 1994; Stagg et al., 2004). A summary of key events and their implications for marine planning purposes is outlined below.

The Northwest Shelf, from Exmouth Gulf to Darwin (Purcell and Purcell, 1988), comprises four major Phanerozoic (550 Ma – present) sedimentary basins of up to 15 km in depth. These include the Bonaparte, Browse, offshore Canning and Carnavorn Basins (Exon, 1994). The outer Northwest Shelf formed as part of East Gondwana during the Palaeozoic (550 – 250 Ma) and subsided during the Late Palaeozoic to form the Westralian Basin on the southern margin of the Tethys Sea (Exon and Colwell, 1994). The superbasin filled with thick Triassic sediments (~235 – 200 Ma) and variable amounts of Jurassic (200 – 154 Ma) sediments before continental break up during the late Jurassic to early Cretaceous (~160 – 100 Ma).

Fluvio-deltaic sedimentation occurred during the late Triassic, and reefal carbonates were deposited on what is now the Exmouth Plateau and Rowley Terrace (Exon and Colwell, 1994). In the middle Jurassic (~175 Ma), before the northern Gondwana break-up, thermal uplift and erosion of the crust occurred and was followed by a period of major faulting and rift volcanism (Exon and Colwell, 1994). Seafloor spreading commenced in the Late Jurassic (~165-161 Ma) and formed the Argo Abyssal Plain and later the Cuvier Abyssal Plain in the Early Cretaceous (~140-136 Ma) (Falvey and Veevers, 1974). The Early Cretaceous break-up of Greater India and Australia controlled much of the development of Exmouth Plateau and Carnarvon Basin (Stagg et al., 1999). After the break-up, subsidence of the distal parts of the margin formed the Exmouth and Scott Plateaus and Rowley Terrace (Falvey and Veevers, 1974). The tectonic framework of the Exmouth Plateau was subsequently controlled by Mesozoic rifting and transform faulting from the break-up (Ramsay and Exon, 1994). A fore-bulge (uplift of the lithosphere) south of the Java Trench developed in the early Miocene (~32 Ma) and created a regional tilt to the south, resulting in north-east inclined faults (Exon and Colwell, 1994). Carbonate masses of rock (bioherms) composed of marine organisms, namely corals and algae, have since accumulated along the fore-bulge.

Tectonic history and basinal settings have controlled the platform morphology, stratigraphic features, depositional sequences, and distribution of the tropical carbonate northwest margin predominantly by maintaining low rates of siliclastic material transfer from the adjacent mainland (Bosence, 2005). Passive margin platforms, such as the Northwest Shelf, are major sites for calcium carbonate accumulation (Bosence, 2005). Following continental breakup of Gondwana, progradation of upper-Cretaceous and Cenozoic carbonates occurred on the outer shelf/slope due to subsidence and the creation of significant accommodation space (Branson, 1978; Exon et al., 1982). Reefs have continued to preferentially develop along the slightly raised rim of the outer shelf/slope (i.e., the Rowley Shoals, Ashmore, Seringapatam, and Scott Reefs).

3.1.3. Oceanography

The NWMR is subject to a variable and energetic oceanic regime that is characterised by the Indonesian Throughflow (ITF) (Gordon and Fine, 1996; Gordon, 2005; Potemra et al., 2003), the Leeuwin Current (LC) (Cresswell, 1991; Holloway, 1995; Holloway and Nye, 1985), internal tides, swell waves, large tides and monsoonal cyclones (Holloway, 1983a; Holloway, 1983b; Ribbe and Holloway, 2001). The ITF flows as a warm mass of saline water at 0.01 – 0.015 km^3s^{-1} that travels south between the Indonesian Archipelago and Australia in response to a steric height gradient in the Pacific (from CSIRO, 2004; Farrand, 1964) (Fig. 3.2.). The ITF impinges onto the Northwest Shelf and contributes to the initiation of the LC (Vranes et al., 2002). The LC is a warm ocean current that flows southwards down the Western Australia coast to Cape Leeuwin where it turns east and travels into the Great Australian Bight (Peter et al., 2005) (Fig.3.2). The LC flow is unlike most eastern boundary currents as it flows in a southerly direction against the dominant wind direction (Godfrey and Ridgway, 1985). The flow is strongest south of North West Cape, where the reduction in shelf width concentrates and intensifies the flow (Holloway, 1995).

The Northwest Shelf is a region characterised by semi-diurnal tides with a spring tidal range that exceeds 6 m in some locations (Easton, 1970). The tidal range increases significantly in magnitude from the Dirk Hartog Shelf to the Sahul Shelf. Tides are <2 m on the inner Dirk

Hartog Shelf, (Nahas et al., 2005), 1.8 m in Exmouth, 2.1 m in Port Hedland, 8.5 m in Broome, 9.2 m in King Sound, and 10.5 m in Collier Bay (Harris et al., 1991; Jones, 1973). Tidal velocities are highest on the inner shelf, and internal tide that generate at the shelf edge during summer months when the water column stratifies move onshore as non-linear waves at speeds of 0.5-1m s^{-1} (Baines, 1981). The shelf bathymetry influences the cross shelf tidal amplification of the region due to an increase in the amplitude of the shelf edge. As the shelf widens and the offshore gradient becomes gentler, significant cross-shelf amplification of the semi-diurnal tide occurs (1.8 m at Exmouth and 9.2 m in King Sound) (Harris et al., 1991; Holloway, 1983b).

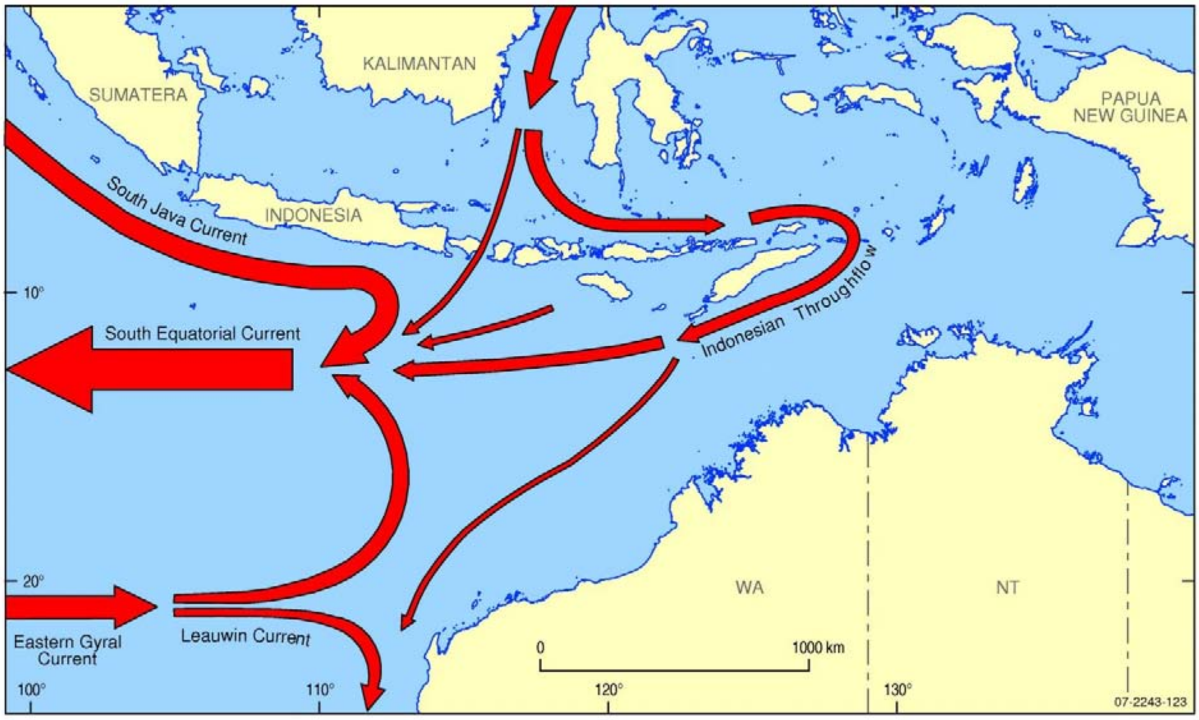


Figure 3.2. Major ocean currents that influence the NWMR (CSIRO, 2004).

The NWMR is an oligotrophic environment (Holloway et al., 1985). Nutrient enrichment of the shelf occurs through river runoff, tidal mixing, internal tides, low frequency circulation, upwelling, and tropical cyclones that induce oceanic mixing and further upwelling (Holloway et al., 1985). The LC maintains warm Sea Surface Temperatures (SST), that inhibit the establishment of macrophyte communities that compete with reef building organisms (Hatcher, 1991) and contribute to the transportation of reef larvae and propagules down the west coast of Australia (Peter et al., 2005). Recorded salinities attain 34.51‰ to 34.75‰ in the Timor Sea (Glenn, 2005), 34.6‰ at Exmouth Plateau (Holloway, 2001), and 35.2‰ to the south of Shark Bay (Woo et al., 2006). The salinity of the Dirk Hartog Shelf is slightly increased because of the transportation of saline water in the LC and the exit of hypersaline water from Shark Bay (Cresswell, 1991; Nahas et al., 2005).

The oceanography of the NWMR plays an important role in regulating sediment transport, deposition and erosion (James et al., 2004). Major contributors to sediment mobilisation include: storm events, including tropical cyclones; internal tides; and ocean currents, including the LC. Tropical cyclones are common in Northwest Australia and are significant agents in the initiation of sediment movement and deposition (Porter-Smith et al., 2004). Internal tides on the

Northwest Shelf lead to the re-suspension and net down-slope deposition of sediment (Ribbe and Holloway, 2001). The LC contributes significantly to the distribution of seabed sediments by transporting terrigenous sediments southwards (Gingele et al., 2001b) and maintaining low rates of nutrient delivery which allows the formation and survival of carbonate reefs south of North West Cape (Hatcher, 1991). Carbonate production on the Rowley Shelf is limited by the seaward flow of saline inner shelf coastal waters (James et al., 2004) (Fig. 3.3.).

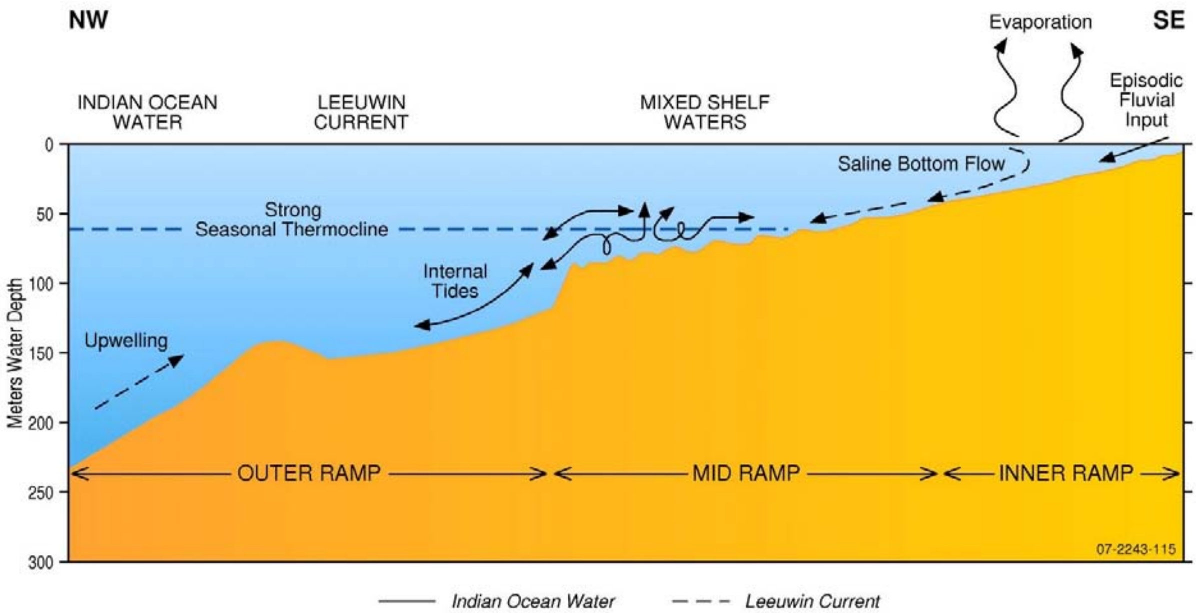


Figure 3.3. Summary diagram of the major oceanographic-climatic factors that affect sedimentation on the ramp that characterises the Northwest Shelf (James et al., 2004).

While oceanography places controls on sediment distribution, the morphological setting of the region impacts the oceanography. The narrowing of the shelf south of North West Cape increases and intensifies the LC, and the broad shelf north of North West Cape allows the propagation of large internal tides (Holloway, 1983a; Holloway, 1983b). A classification of the Australian shelf based on sediment threshold values has identified dominant areas of tide- and/or wave-induced sediment transport (Porter-Smith et al., 2004). The inner shelf area north of Dampier is either wave only or tidal dominated, the broad outer shelf north of Dampier tide only, and the shelf south of Dampier wave dominated (Fig. 3.4) (Porter-Smith et al., 2004).

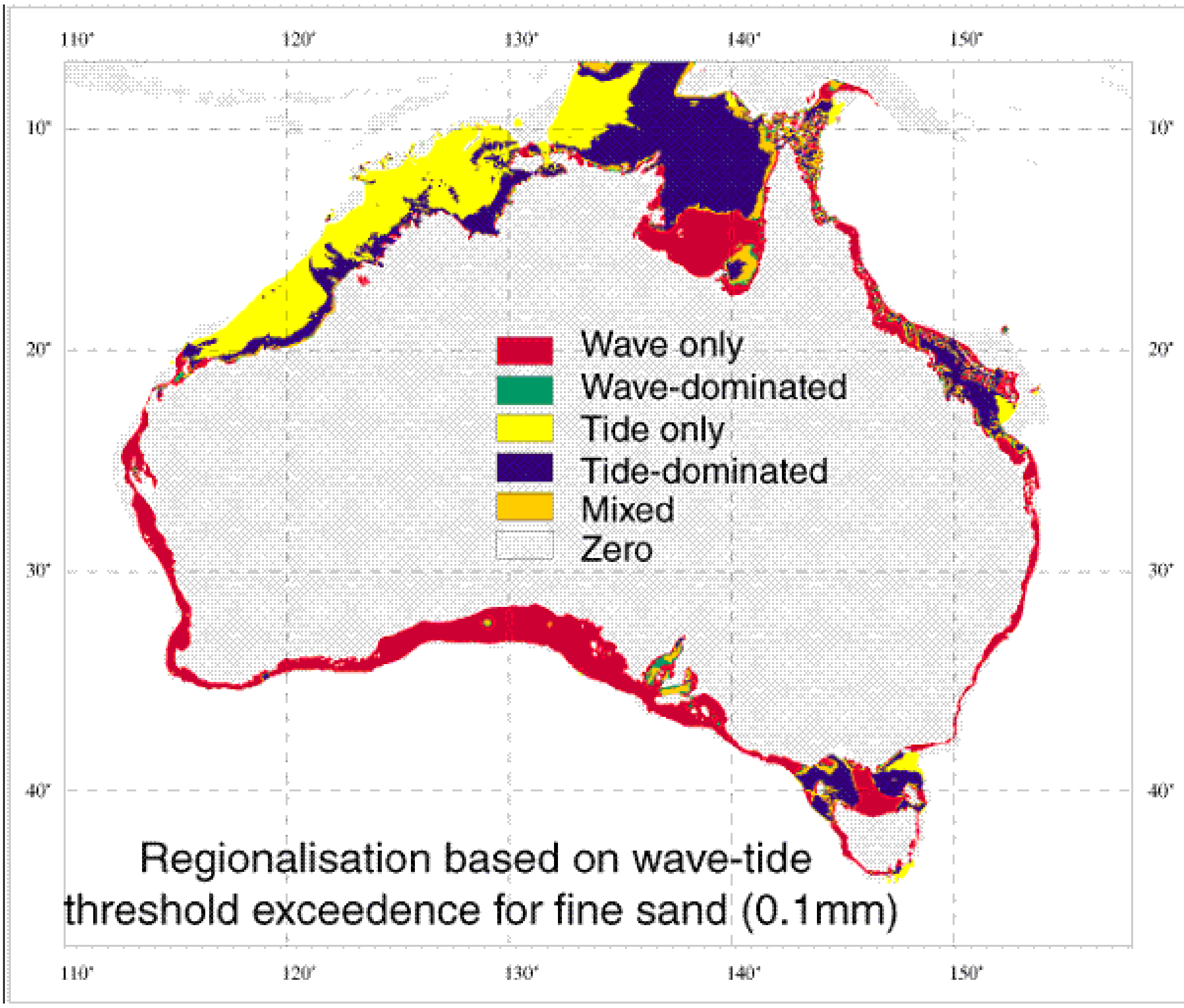


Figure 3.4. Regionalisation of the Australian continental shelf for fine sand (0.1mm) distribution calculated from wave and tide exceedence estimates (Porter-Smith et al., 2004).

3.1.4. Late Quaternary (Holocene) Evolution

The late Quaternary evolution of the NWMR is characterised by a fluctuating climate, oceanography and sea level, which is reflected in seabed sediments and geomorphic features of the region. During the Last Glacial Maximum (LGM) at around 20 ka BP, sea level was ~ 110-130 m lower than present (Harris et al., 1991; van Andel et al., 1967; Woodroffe, 2000). The shelf was sub-aerially exposed, arid, and covered with savannah vegetation (Fleming et al., 1998). SST's were lower, evaporation was reduced and the southward flowing LC weakened and/or arrested (Okada and Wells, 1997). Rapid sea level rise from 18 ka to 8 ka BP (Curray, 1961) and gradual rise thereafter submerged the shelf area until sea level reached its present elevation. These late Quaternary adjustments assisted in the growth and development of reef building organisms, left drowned terraces and steps along the outer shelf (at ~ 60, 65, 75, 190, 280, 360 m, and the most prominent at 120 m water depths) (Harris et al., 1991; Jones, 1973), and stranded carbonate sediments on the middle shelf (James et al., 2004).

During the LGM, the NWMR was subject to cooler SST's, climatic conditions and a weaker LC (van der Kaars, 1991; Wells and Wells, 1994). Large areas of anomalously cool water were widespread (Prell et al., 1980), and SST was reduced by 6-7°C off North West Cape (Wells et al., 1994). These cool sea surface temperatures and the associated strong offshore winds from Western Australia combined to create strong bottom upwelling (Okada and Wells, 1997) that resulted in increased surface productivity during the LGM (Wells et al., 1994). The volume and intensity of the LC decreased and/or ceased at the LGM and has subsequently increased during the non-glacial period (Gingele et al., 2001b). The increase in flow has subsequently prevented and/or limited oceanic upwelling and has contributed to low productivity levels in the region.

The distribution of seabed sediments in the NWMR reflects the late Quaternary evolution of the region. Shallow-water calcium carbonate production was active during the Pleistocene to early Holocene along much of the Northwest margin. Production on the shelf was dominated by ooids and smaller amounts of *Halimeda* but was unable to keep pace with the rising sea levels of the late Quaternary (Dix et al., 2005). As a result the sediments are currently localised to the mid shelf. The most prominent of these are ooids and peloids that formed at 15.4-12.7 ka BP in the saline waters of post glacial sea level rise (James et al., 2004). The initiation of the LC arrested ooid production and resulted in the accumulation of biofragmental benthic Holocene sediment that is now localised to the inner shelf and to a ridge of planktonic foraminifera offshore (James et al., 2004). Today, carbonate production is limited due to the strengthening of summer rains, increased volume of siliclastic input, and the initiation of the LC that occurred during the Holocene (Dix et al., 2005).

Modern coral reefs of the NWMR began as coral communities that formed substrata during the Holocene marine transgression (Hatcher, 1991). These include the Ningaloo and Ashmore Reefs (Fig. 3.12). Ashmore Reef is located at the shelf edge, and the Holocene section began growth at 7.5 ka BP in response to the changing ocean and climate conditions (Glenn and Collins, 2005). The following sequence of events, summarised from the model of Ashmore Reef growth (Glenn and O'Brien, 1999; Glenn and Collins, 2005), is considered to characterise regional Holocene development on the margin:

- 7.5-6.5 ka BP: reef growth began with an initial vertical growth phase that recolonised the underlying Pleistocene strata and kept pace with rising sea levels;
- 6.5-4.5 ka BP: a transitional phase of reef growth occurred as the reef caught pace with slowly rising sea levels; and
- 4.5 ka BP – to present: the reef extended laterally as the reef flats became more pronounced, wider and productive. Infilling of the reef lagoons occurred as mobile intertidal sand flats began to form.

The Ningaloo Reef is located on the inner shelf and similarly took on its present form during the Holocene. The Holocene section recolonised the last interglacial reef at North West Cape at 7.57 ka (Collins et al., 2003).

3.1.5. Geomorphology

The NWMR comprises an extensive array of geomorphic features and provinces and contains 19 of the 21 geomorphic identified for Australia's EEZ (Heap and Harris, in press-b). Geomorphic features within the region and their coverage are summarised in Section 4. Prominent geomorphic features include the Exmouth Plateau (Stagg et al., 2004), Carnarvon Terrace (Heggie et al., 1993), Rowley Terrace (Stagg and Exon, 1981), Scott Plateau (Stagg, 1978), King Sound Basin (Semeniuk, 1980; Semeniuk, 1981; Semeniuk, 1982), Cuvier Abyssal Plain, Argo Abyssal Plain (Buffler, 1994), Ashmore Reef (Glenn and O'Brien, 1999; Glenn and Collins, 2005), Scott Reef, Rowley Shoals and Ningaloo Reef (Collins et al., 2003). Key geomorphic features and their place names are displayed in Figure 3.5 and Table 3.1.

A total of four shelf divisions are recognised within the region: Dirk Hartog, Rowley, Northwest, and Sahul Shelves (Harris et al., 2003; Heap and Harris, in press-b). The shelf width increases northwards and the broad Sahul Shelf extends continuously to Indonesia. At North West Cape, the Dirk Hartog Shelf reaches the minimum shelf width of the Australian continental margin at ~7 km. Two main abyssal plains/deep ocean floor features lie within the NWMR, and these extend well beyond the boundary of Australia's EEZ. An extensive series of carbonate banks and coral reefs are located within the NWMR. The outer Northwest Shelf is deposited with a string of submerged carbonate banks and these include the Ashmore Reef (Glenn and O'Brien, 1999; Glenn and Collins, 2005), Cartier Island and Seringapatam Reef. Reefs of the inner shelf are dominated by hard corals and include the Dampier Archipelago, Bonaparte Archipelago and Ningaloo Reef (Collins et al., 2003).

A detailed account of the geomorphology for the inner shelf, middle shelf, outer shelf and continental slope, and abyssal plain/deep ocean floor is described in the synthesis of literature that follows.

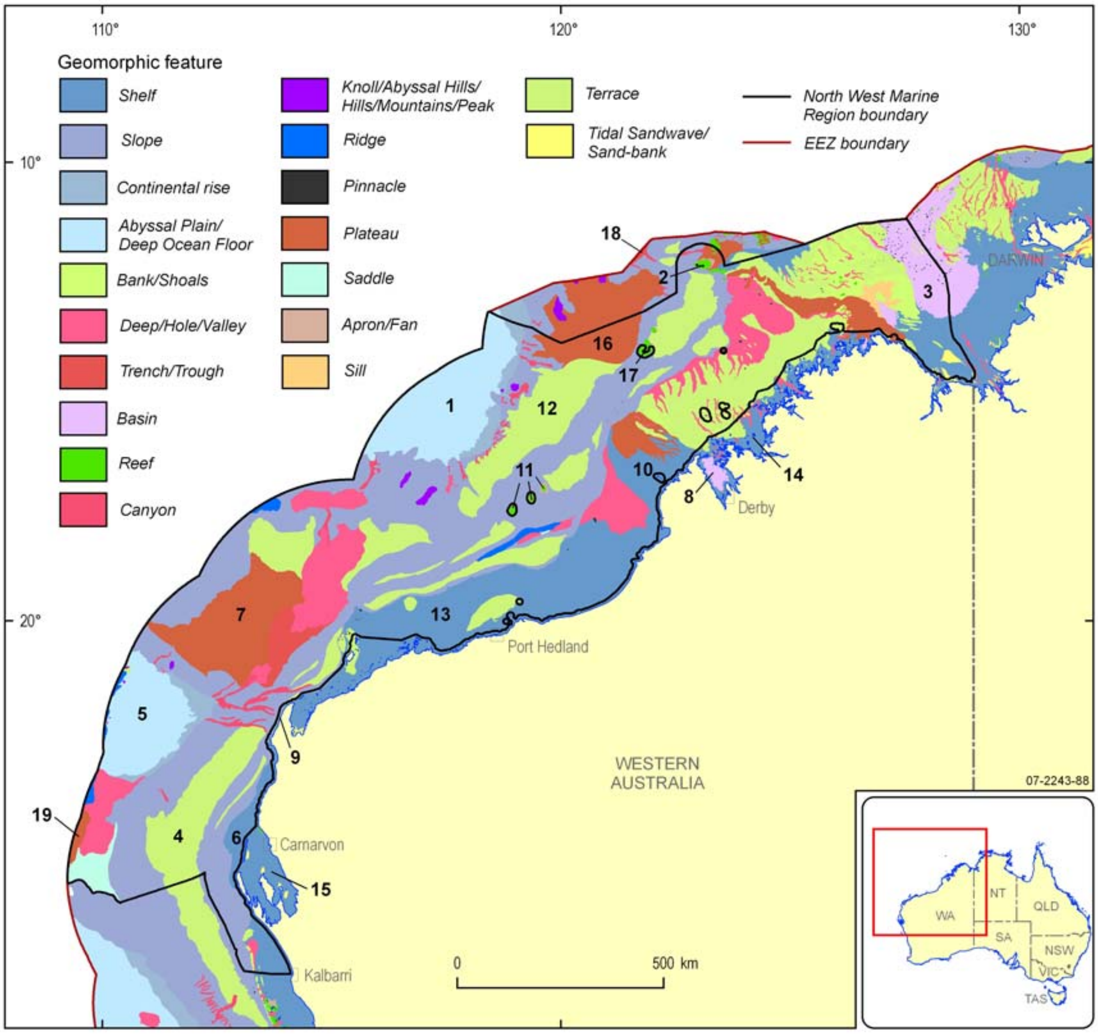


Figure 3.5. The geomorphic features of the NWMR as identified by Heap and Harris (in press). Numbers 1 to 19 refer to key place names which are provided in Table 3.1.

Table 3.1. Place names and associated references for geomorphic features displayed in Figure 3.1.

No.	Geomorphic Feature	Feature Type	References
1	Argo Abyssal Plain	Abyssal Plain (1)	Buffler (1994); Falvey & Veevers (1974)
2	Ashmore Reef	Reef (2)	van Andel & Veevers (1967); Glenn & Collins (2005)
3	Bonaparte Depression	Valley (3)	Lees (1992); van Andel & Veevers (1967)
4	Carnarvon Terrace	Terrace (4)	Symonds & Cameron (1977)
5	Cuvier Abyssal Plain	Abyssal Plain (5)	Colwell et al., (1994)
6	Dirk Hartog Shelf	Shelf (6)	Dix (1989); Dix et al., (2005)
7	Exmouth Plateau	Plateau (7)	Colwell & von Stackelberg (1981); Stagg (1978)
8	King Sound	Basin (8)	Carrigy & Fairbridge (1954)
9	Ningaloo Reef	Reef (9)	Collins et al., (2003)
10	Northwest Shelf	Shelf (10)	Jones (1967; 1970; 1973)

11	Rowley Shoals	Reef (11)	Carrigy & Fairbridge (1954); Jones (1973)
12	Rowley Terrace	Terrace (12)	Falvey & Veevers (1974); Stagg (1978)
13	Rowley Shelf	Shelf (13)	Carrigy & Fairbridge (1954)
14	Sahul Shelf	Shelf (14)	Carrigy & Fairbridge (1954)
15	Shark Bay	Shelf (15)	Woo et al., (2006)
16	Scott Plateau	Plateau (16)	Falvey & Veevers (1974); Stagg (1978)
17	Scott Reef	Reef (17)	Jones (1973)
18	Timor Trough	Trench/Trough (18)	Veevers et al., (1978)
19	Wallaby Plateau	Plateau (19)	Falvey & Veevers 91974); Sayers et al., (2002)

3.1.5.1. Inner Shelf

The inner shelf occurs in water depths of <30 m and covers an area of ~140,000 km^2 (Fig.3.1). It includes prominent areas such as Shark Bay, Ningaloo Reef, and King Sound Basin. Of the three shelf divisions of the NWMR, the Dirk Hartog Shelf occurs mostly in the inner shelf region. The Dirk Hartog Shelf is narrow (~7 km at Ningaloo Reef) with shallow water depths (0-100 m) that concentrate and intensify the LC.

Tidal sand waves/sandbanks are present in the innermost reaches of the Exmouth Gulf and at the entrance to and within the vicinity of Shark Bay. Sand waves combined with seagrass banks in Shark Bay reduce water circulation in the bay and dramatically increase its salinity (Harris et al., 1991). As a result the bay is hyper-saline, and its outflow increases the salinity of the LC (Woo et al., 2006).

Ningaloo Reef is situated off North West Cape and extends for 260 km while maintaining a distance of 1-6 km from the shoreline (Harris et al., 2003). The reef represents the world's largest fringing coral reef and is composed of Holocene reef growth recolonised on an antecedent (Pleistocene) reef basement (Collins et al., 2003). Holocene reef growth occurs predominantly in water depths <30 m and is dominated by robust coral due to the year round exposure to a relatively high wave climate (Collins et al., 2003).

To the south of the Sahul Shelf lies King Sound. The embayment occupies an area of 2,500 km^2 and contains extensive mud flats that are extensively inhabited by mangrove growth (Carrigy and Fairbridge, 1954). The embayment experiences some of the largest tides on the shelf at ~9.2 m (Semeniuk, 1980).

3.1.5.2. Middle Shelf

The middle shelf covers an area of 530,000 km^2 with water depths that range from 30 – 200 m (Fig. 3.1). The middle shelf environment covers the majority of shelf within the NWMR. Prominent geomorphic features of the region include terraces, deeps/holes/valleys, ridges, plateaus and pinnacles. The middle shelf includes the Dirk Hartog, Rowley/Northwest and Sahul Shelves. Available data indicates that the seabed of the Rowley/Northwest Shelf is gentle and smooth while the Sahul Shelf has a complex topography. The Sahul Shelf consists of a series of rises, depressions, banks, terraces and channels (van Andel and Veevers, 1967). Terraces and plateaus are located on the middle shelf and are considerably smaller in size than the larger terraces and plateaus located on the outer shelf/slope.

The Bonaparte Depression is a broad depression located on the middle Sahul Shelf and is bound by the Londonderry and Sahul Rises. The depression comprises a 45,000 km^2 basin that forms an epicontinental sea with a maximum water depth of 155 m (Lees, 1992). The eastern flank of the depression is steep, the western flank very gentle and the south merges into a broad, featureless plain (van Andel and Veevers, 1967). The floor of the depression is relatively flat and punctured by numerous pinnacles and subaqueous banks (Harris et al., 2003). The depression is bounded by the Londonderry, Sahul and Van Diemen Rises (Fig. 3.16). The Matila Shelf Valley is a long, narrow, curved channel that connects the Bonaparte Depression with the Timor Trough and is fringed with small, steep, carbonate banks (van Andel and Veevers, 1967).

Other prominent geomorphic features that occur on the middle shelf include small terraces, deeps/holes/valleys, and trench/troughs. Small terraces parallel to the coast are located on the Rowley Shelf. A larger terrace is situated on the Sahul Shelf and is dissected by a series of deep valleys with a N-W orientation (Harris et al., 2003).

3.1.5.3. Outer Shelf and Slope

The outer shelf and slope extend from ~200 m water depth to the abyssal plain/deep ocean floor at ~4000 m water depth (Fig. 3.1). No distinct shelf break is recognised; rather there is a smooth transition from the outer shelf to the upper slope. The outer shelf/slope is an extensive area of the NWMR and covers 930,000 km^2. Prominent geomorphic features of the outer shelf/slope are the Exmouth Plateau, Scott Plateau, Rowley Terrace, Carnarvon Terrace, areas of knoll/abyssal hills/hill/mountains/peak, and a series of carbonate reefs and algal deposits.

Two large terraces are located on the outer shelf/slope region of the NWMR. These terraces are larger than the terraces located on the middle shelf, run parallel to the coast and include the prominent Carnarvon and Rowley Terraces (Fig. 3.6). The Carnarvon Terrace extends for 800 km to the south of North West Cape, covering an area of 80,000 km^2 of which 60,000 km^2 is within the NWMR. The terrace is located to the east of the Wallaby Plateau and forms a shallow zone on the upper slope (Harris et al., 2003). The Rowley Terrace is located on the slope of the Rowley Shelf and occupies an area of 42,000 km^2.

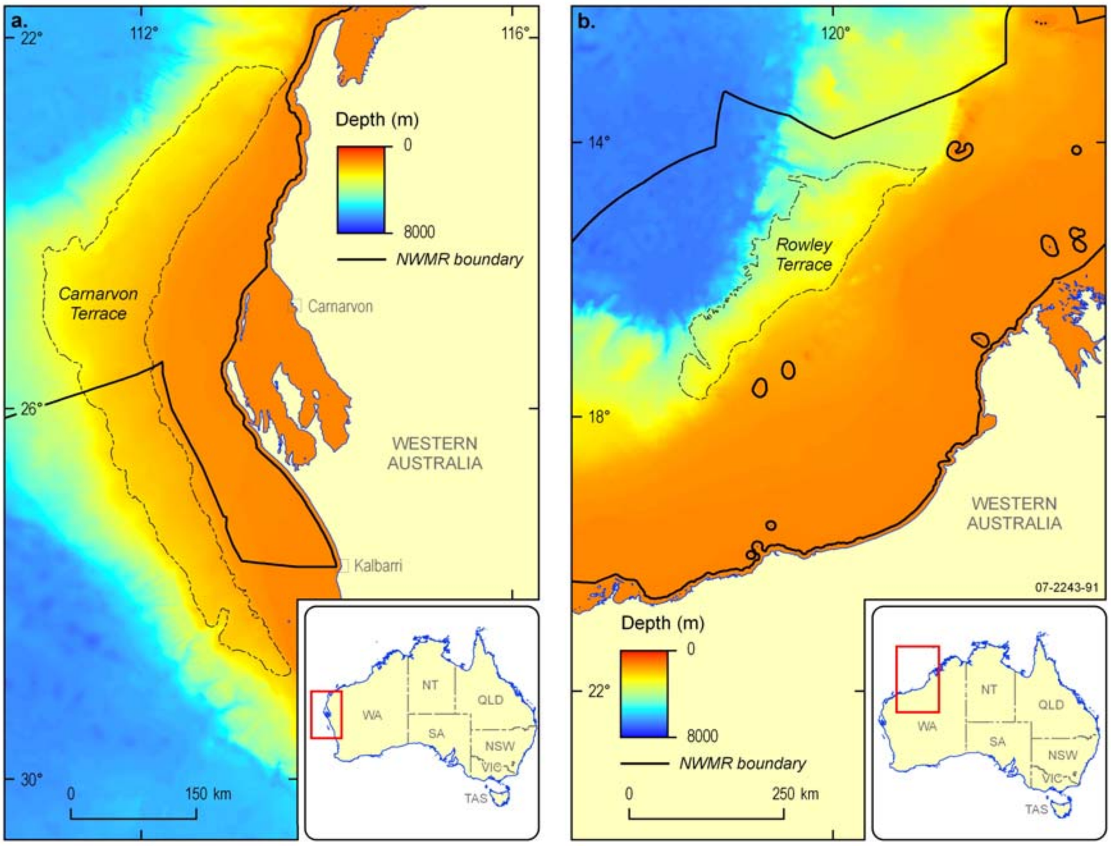


Figure 3.6. Bathymetry of, a) Carnarvon Terrace; b) Rowley Terrace.

Three plateaus are situated on the outer shelf/slope region of the NWMR (Exmouth; Wallaby; and Scott) (Fig. 3.7). The Exmouth Plateau is the smallest, covering an area of ~5,000 km^2, while the Wallaby and Scott Plateaus occupy an area of 70,000 km^2 (Sayers et al., 2002) and 80,000 km^2, respectively. Approximately 2,500 km^2 of the Wallaby and 42,000 km^2 of the Scott Plateau lie in the NWMR. The Wallaby Plateau is bounded to the south by the NW-trending Wallaby-Perth Scarp (the Wallaby-Zenith Fracture Zone) (Harris et al., 2003).

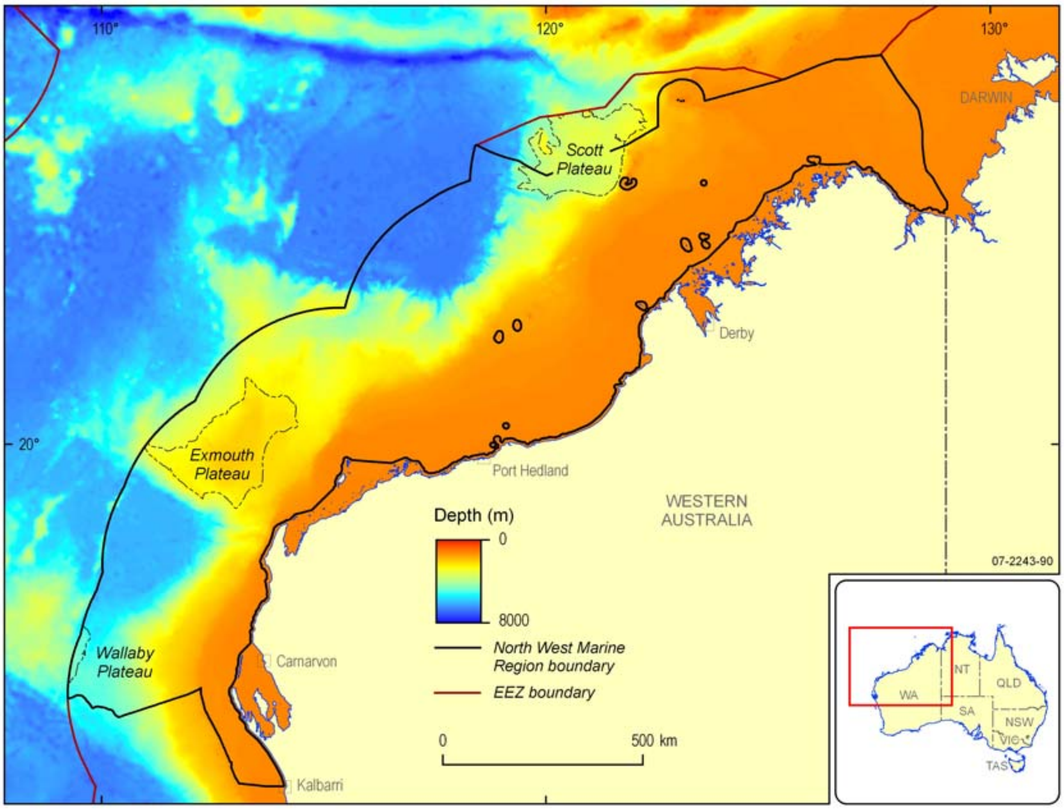


Figure 3.7. Bathymetry and location of the Wallaby, Exmouth and Scott Plateaus.

Carbonate reefs are located along the outer shelf, and their presence indicates subsidence of the shelf edge (Teichert and Fairbridge, 1948). These include the Ashmore, Adele, Browse, Cartier, Seringapatam and Scott Reefs and the Rowley Shoals (Fig. 3.8). Present day coral reefs north of the Ashmore Reef are mostly composed of coralline algae such as *Halimeda*, while south of and including Ashmore Reef they are principally composed of scleractinian corals (Harris et al., 2003). A series of drowned carbonate banks are located at the edge of the Sahul Shelf. These banks are generally 10 km^2 in area with flat tops (developed as terraces and benches), and contain steep slopes of ~20° (van Andel and Veevers, 1967).

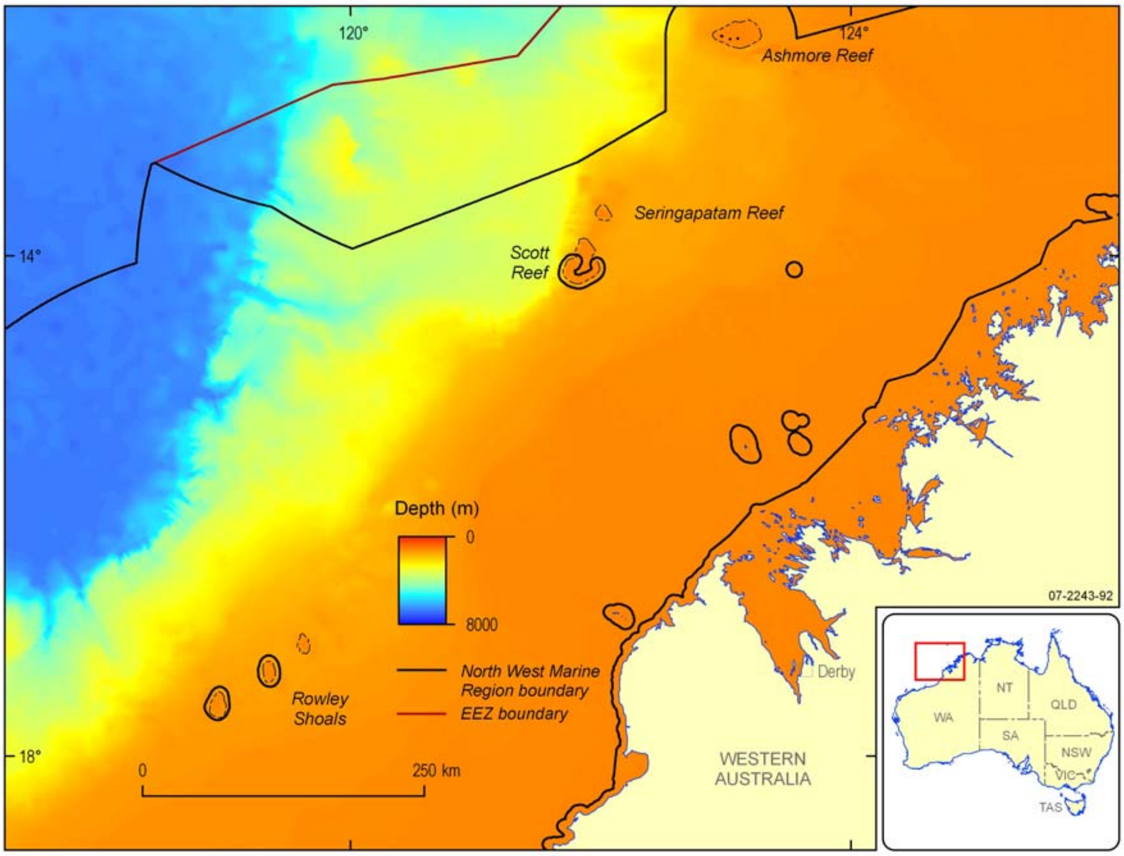


Figure 3.8. Bathymetry and location of the Rowley Shoals, Scott, Seringapatam, and Ashmore Reefs.

The Rowley Shoals are a chain of coral reefs with similar dimensions, shape and orientation and are situated on the slope to the west of the Rowley Shelf (Harris et al., 2003). The shoals are N-S orientated and rise vertically from 440 m water depth (Jones, 1973). The reefs consist of a thick, coral-rich Holocene stratum overlying a Pleistocene (and probably older) reef basement and are located within the headwaters of the southward flowing Leeuwin Current (Hatcher, 1991). Scott Reef is located on the slope to the east of the Scott Plateau and occupies an area of 800 km^2. Scott Reef rises from a depth of ~450 m (Jones, 1973) and consists of two separate atolls (North Reef and South Reef) that are divided by a channel of ~400 m water depth. Ashmore Reef is situated on the slope adjacent to the Sahul Shelf and occupies an area of 720 km^2. The reef is composed of sub-aerial islands that cover an area of 0.55 km^2. The reef is ovoid in shape and lies in water depths <300 m. The southern margin of Ashmore Reef is more robustly developed than the northern margin due to its exposure to an energetic southeast wind and swell regime (Glenn and Collins, 2005).

3.1.5.4. Abyssal Plain/Deep Ocean Floor

The abyssal plain/deep ocean floor of the NWMR lies in water depths of 4,000-6,000 m. The abyssal plain/deep ocean floor is separated into the Cuvier and Argo Abyssal Plains located to the west of the Dirk Hartog Shelf and to the north of the Rowley Shelf, respectively (Fig. 3.9). A total area of 40,000 km^2 of the Cuvier Abyssal Plain and 60,000 km^2 of the Argo Abyssal Plain are located in the NWMR.

The Argo Abyssal Plain lies in water depths of >5,000 m and forms an area of low relief (Harris et al., 2003). The plain is bounded predominantly by slope with a small portion (11,500 km^2 in the NWMR) of rise to the east. Rise also occurs south of the Exmouth Plateau and forms a smooth sediment apron, while northwest of the Exmouth Plateau the surface is rough and undulating (Harris et al., 2003). The surface of the abyssal plain slopes gently to the north and forms the outer ridge to the Java Trench (Buffler, 1994; Falvey and Veevers, 1974). Swales are present in the southwest regions of the plain, and small hills have been identified on the western margin (Harris et al., 2003).

The Cuvier Abyssal Plain is also situated in water depths >5,000 m. The plain is bounded by the Wallaby Plateau to the southwest and the rise to the east. The Cuvier Abyssal Plain deepens to the northwest and forms a possible subaqueous drainage system into the Wharton Basin at 20°S and 108.5°E (Harris et al., 2003). Two prominent ridges trend from the north to northeast from the Wallaby Plateau into the Cuvier Abyssal Plain (Colwell et al., 1994b)

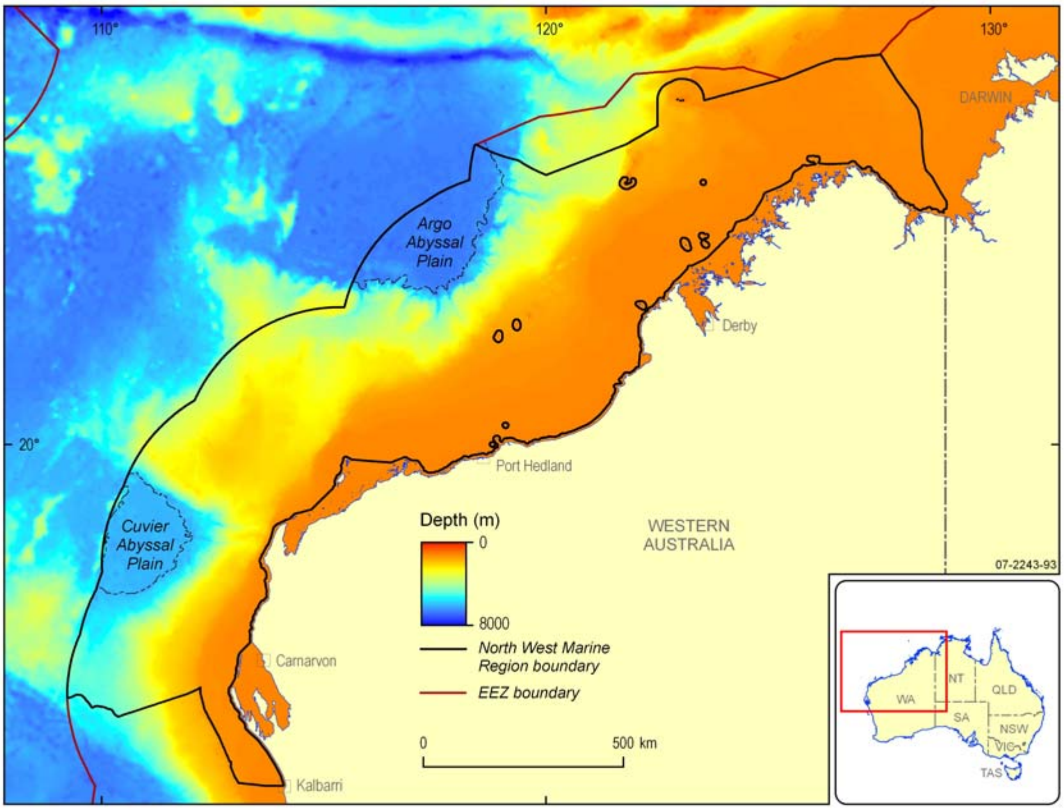


Figure 3.9. Location and bathymetry of the Cuvier and Argo Abyssal Plains.

3.1.6. Sedimentology

Seabed sediments of the NWMR comprise bio-clastic, calcareous and organogenic sediments that were deposited by relatively slow and uniform sedimentation rates (Carrigy and Fairbridge, 1954) (Fig. 3.10). The region is a zone of sediment bypass and winnowing rather than one of active deposition (Jones, 1971). Sediments grade from sands and gravels on the shelf to muds on the slope and abyssal plain/deep ocean floor (Colwell and Von Stackelberg, 1981).

Calcium carbonate deposits are located on the inner shelf, middle shelf and outer shelf/slope. Terrigenous sediments constitute a minor component and occur most frequently within areas of the inner shelf adjacent to rivers.

A variety of processes control the sediment transport mechanisms of the inner shelf, middle shelf, outer shelf/slope and abyssal plain/deep ocean floor. The inner shelf is influenced by the outflow of terrigenous sediments from rivers. Sediments of the middle shelf region are predominantly influenced by tidal processes, including internal tides. Sediments of the outer shelf/slope are influenced through a combination of slope processes and large ocean currents. These processes and their impact on seabed sediments in NWMR are described below (Section 3.1.6.1-3.1.6.2).

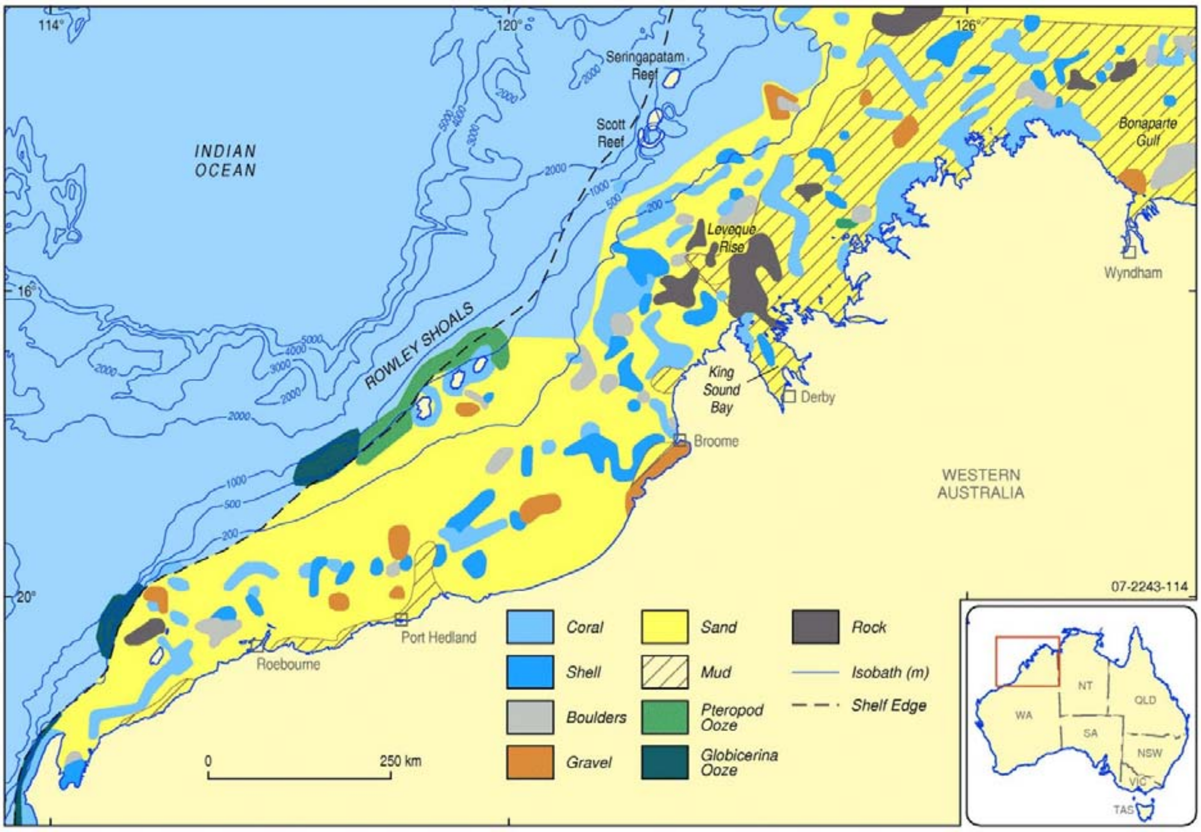


Figure 3.10. Sedimentary facies model of the northwest shelf (Carrigy and Fairbridge, 1954).

3.1.6.1. Inner Shelf

The sedimentology of the inner shelf is characterised by sand, with localised accumulations of mud and gravel. These localised deposits occur at Roeburne, Broome and to the north of the Leveque Rise (Carrigy and Fairbridge, 1954) (Fig 3.10). Sediments of southern inner shelf are mostly carbonates comprising skeletal fragments and lithoclasts (Dix, 1989). Coral fragments are most common southwest of Dampier where fringing reefs have formed a veneer on the Pleistocene basement (Dix et al., 2005). Silt-sized sediments of the Northwest Shelf contain 30% carbonate and 70% siliclastic (non-carbonate) sediments with benthic skeletal fragments that include bivalves, gastropods, sponge spicules, foraminifera and bryozoans (Dix et al., 2005). Planktonic foraminifera occur extensively along the inner shelf and reflect the absence of an oceanic barrier along the shelf (Dix et al., 2005). *Halimeda* grows on hard substrates in the Dirk

Hartog Shelf however but is absent in unconsolidated sediment of the Dirk Hartog Shelf (James et al., 1999) (Fig. 3.11.).

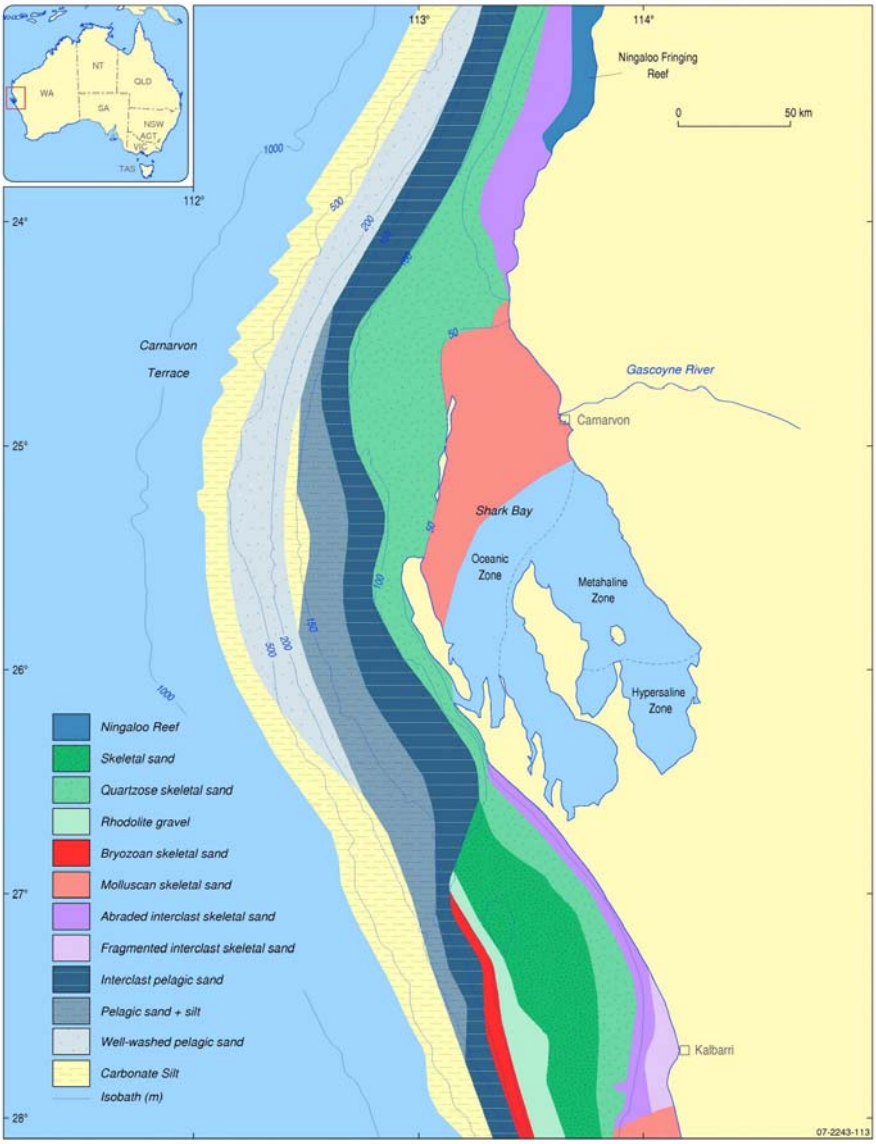


Figure 3.11. Sedimentary facies model of the Dirk Hartog Shelf (James et al., 1999).

Terrigenous sedimentation of the inner shelf is generally low and varies depending on its proximity to rivers. The Sahul Shelf receives most of the terrigenous input of the inner shelf zone, and consequently, terrigenous sediments constitute a moderate component of the seabed sediment (Carrigy and Fairbridge, 1954). The absence of rivers adjacent to the Rowley Shelf has resulted in negligible accumulations of terrigenous sediments on the seabed. The terrigenous component of sediments on the inner Dirk Hartog Shelf contain 30-60% terrigenous grains due to its close proximity to the Gascoyne River (James et al., 1999). These sediments are generally limited to and trapped in estuaries and embayments (Carrigy and Fairbridge, 1954).

Deposition of seabed sediments on the inner shelf is controlled by tidal currents; inner shelf currents, generated by the interaction of water with the underlying rocks and reefs; cyclones; and sediment reworking through winds, tides and waves (Dix, 1989). These interactions have resulted in the deposition of coarse grained (<3 wt % mud) sediments and sand bodies of up to

50 m thickness on the Northwest Shelf (Dix, 1989). The inner Sahul Shelf sediments are gravel and sand dominated, and the area is a zone of sediment bypass where high tidal velocities result in deep erosion (Lees, 1992). Sediment transport and deposition is influenced by the coastal turbidity zone which results in the trapping and suspension of fine terrigenous sediments in close proximity to the coast.

3.1.6.2. Middle Shelf

Seabed sediments of the middle shelf are dominated by sand with accumulations of coral and gravel deposits (Carrigy and Fairbridge, 1954) (Fig. 3.12). Sand dominates the middle shelf and comprises skeletal fragments with a high proportion of relict grains (>30%). These relict grains are most prominent on the Northwest Shelf where sediments are a variable mixture of relict, stranded and Holocene grains (James et al., 2004). A high concentration of mud with localised bands of sand and gravel occur along the Sahul Shelf (Carrigy and Fairbridge, 1954). Shallower (~ 70 m water depth) parts of the Dirk Hartog Shelf are covered with medium to coarse grained sands while deeper areas (~70-100 m water depth) contain poorly sorted sediments (James et al., 1999). Prior to the present study, the seabed sediments of the region were known to be relatively coarse and sand dominated, with ~90% calcium carbonate content and relict material distributed throughout (Jones, 1970; Jones, 1973).

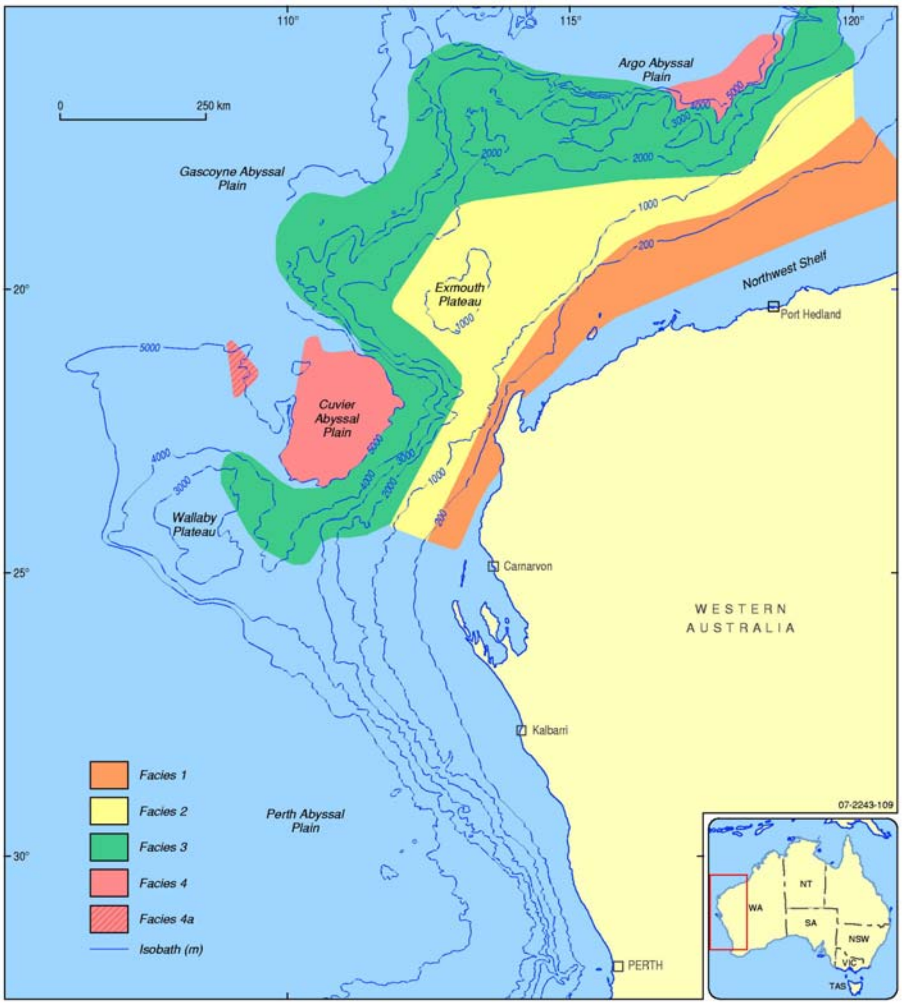


Figure 3.12. Sediment facies of the northwest margin, facies 1) shell fragments, pteropods, benthic and planktonic foraminifera; facies 2) pteropods, planktonic foraminifera; 3) planktonic foraminifera; facies 4) radiolarian, diatoms, partly dissolved planktonic foraminifera (Colwell and Von Stackelberg, 1981).

The Northwest Shelf is characterised by an extensive accumulation of relict Holocene grains that were stranded during the marine transgression (Dix et al., 2005). This Holocene sedimentary deposit has been extensively documented by James et al (2004) and consists of relict intraclasts, both skeletal and lithic, that formed during sea-level highstands of Marine Isotope Stages 3 and 4. The most notable of these sediments are ooids and peloids that formed 15.4-12.7 ka BP (James et al., 2004) (Fig. 3.13). Seasonal evaporation on the inner shelf creates a seawards movement of bottom water that has limited the present day production of calcium carbonate on the middle shelf (James et al., 2004).

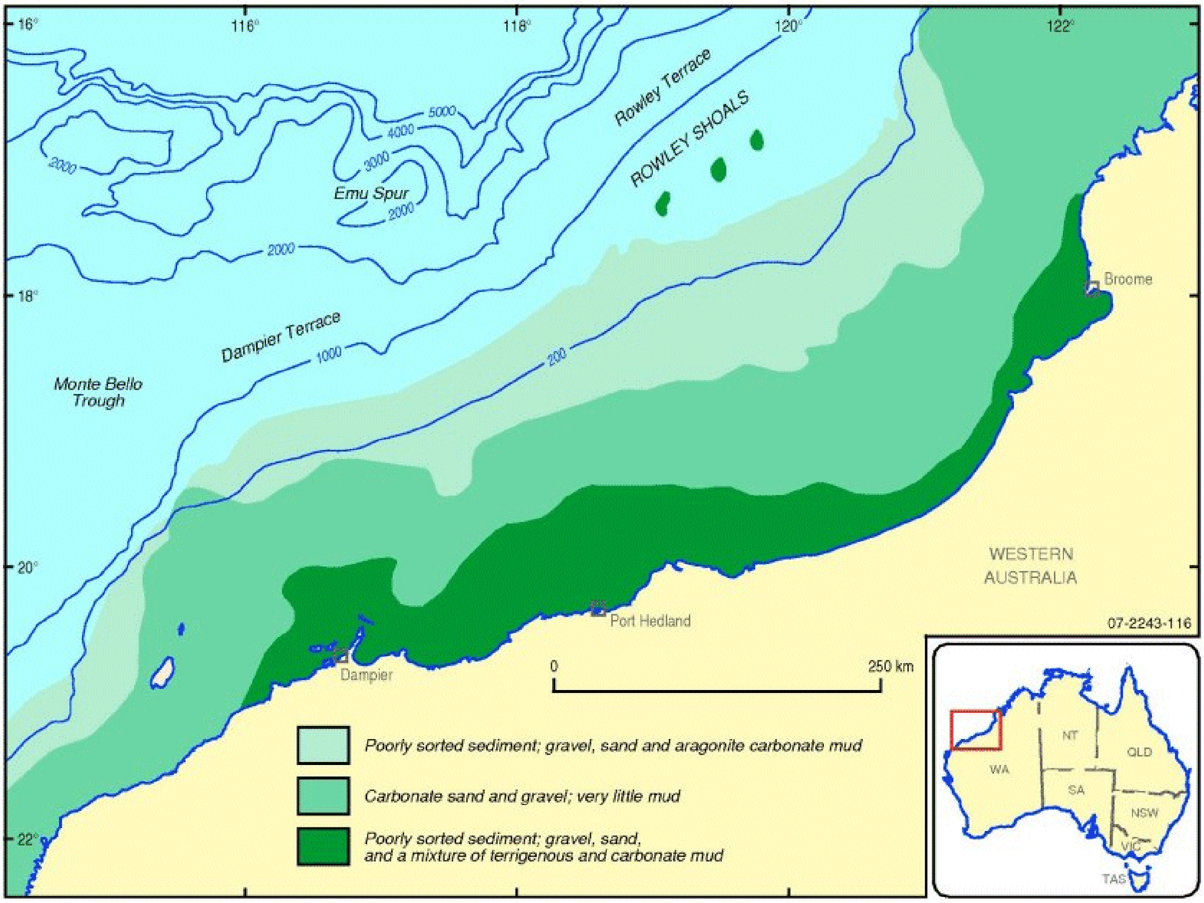


Figure 3.13. Seabed sediments of the Northwest Shelf (James et al., 2004).

Sediment transport on the middle shelf is influenced by a combination of processes from the inner and outer shelf including winds, tides and waves, coastal turbidity, and slope processes. Sediments are reworked through a combination of tidal and wave currents (Dix et al., 2005) and well-polished through continual wave abrasion (James et al., 1999).

3.1.6.3. Outer Shelf and Slope

The outer shelf and slope is dominated by fine grained sediments (Jones, 1973) with thicker accumulations of carbonate deposits at the shelf edge. Carbonate mud constitutes a major component of the sediment and contains modern pelagic ooze and aragonitic needle-rich micrite (Dix et al., 2005). An extensive series of carbonate reefs located on the outer shelf are surrounded by deposits of coarse and fine coraligenous clastics (Carrigy and Fairbridge, 1954). The sand fraction of sediments of the outer shelf consists mainly of planktonic foraminifera and is bounded by a belt of rapidly deposited silt-sized carbonate and terrigenous sediment (Jones, 1973). Further seawards, on the slope, slower rates of sedimentation occur and result in an increase in the proportion of sand-sized planktonic foraminifera (Jones, 1973). Small pellets (0.1 mm in diameter) are located on slope of the Northwest Shelf and these are either faecal in origin or are turbid micrite clasts of small planktonic foraminifera (Jones, 1973).

Sediment from the Exmouth Plateau consists mainly of foraminiferal ooze and sand composed of 20-60% sand and 60-75% calcium carbonate grains (Colwell and Von Stackelberg, 1981). The fine fraction of the surficial sediment consists of planktonic foraminifera (Colwell and Von Stackelberg, 1981). Benthic mollusc fragments, pteropod shells, and planktonic and benthic foraminifera constitute the major skeletal component (Colwell and Von Stackelberg, 1981). The sedimentology varies in composition with water depth and reflects the abundance of biogenic components. As water depth increases, the sediment grades from calcareous oozes and sands to siliceous clays (Colwell and Von Stackelberg, 1981). The high proportion of sand in the sediments suggests winnowing of finer material by bottom currents (Colwell and Von Stackelberg, 1981). The distribution of clay minerals in contours suggests the outer slope is affected by the Western Australia (WAC) and Eastern Gyral Currents (EGC) (Figure 3.2) (Gingele et al., 2001a).

Seabed sediments of the Timor Trough are predominantly composed of silty clays separated from the Sahul Shelf by a narrow band of sandy-silty clay at the top of the continental slope (van Andel and Veevers, 1967). Calcarenite clays occur in deep water regions and contain planktonic foraminifera (van Andel and Veevers, 1967). The carbonate content of sediments ranges from 15-100%, is dependent on grain size, and varies along a gradient from ~75-100% carbonate content on the outer shelf to ~0-50% comprising calcareous clays near the island of Timor (van Andel and Veevers, 1967).

The texture and composition of sediments of the outer shelf and slope are influenced by bottom currents, oceanic upwelling, and large scale currents such as the WAC, EGC and LC.

3.1.6.4. Abyssal Plain/Deep Ocean Floor

Seabed sediments of the abyssal plain/deep ocean floor are dominated by fine grained sediment. Due to the difficulty obtaining sediments from the area, knowledge of seabed sediments is limited in comparison to that of the shelf and slope. The Deep Sea Drilling Program (Deep Sea Drilling Program Initial Report; 27) has collected two cores from abyssal plains offshore Western Australia and the composition of one core from the Argo Abyssal Plain is stored in the MARS database. This sample contains 86% mud and less than 1% calcium carbonate. Veevers et al (1974) analysed this sample and showed that seabed sediments of the Argo Abyssal Plain are composed of a thin section of Cainozoic ooze and clay.

The basement of the Cuvier Abyssal Plain is overlain by a horizontal unit of well-stratified sediments (Deep Sea Drilling Initial Report; 27). The Cuvier Abyssal Plain receives significant amounts of terrigenous sediment sourced from the continent which is then debouched onto the deeper Wharton Basin (Harris et al., 2003). In general, seabed sediments of the deep ocean grade from sands to siliceous clays with increasing water depth (Colwell and Von Stackelberg, 1981). The calcium carbonate content of sediments on the abyssal plain/deep ocean floor is negligible because the area lies below the carbonate compensation depth of 4,500-5,000 m (Colwell and Von Stackelberg, 1981).

3.2. THE NOMINATED AREA OF THE NORTHERN MARINE REGION

3.2.1. Introduction

The nominated area of the Northern Marine Region (NNMR) extends from the Bonaparte Gulf in the west to Aurari Bay in the east. The region covers an area of 161,000 km^2 and is contained within the larger Northern Marine Region (NMR). The tectonic history, oceanography, Late Quaternary evolution, geomorphology and surficial sedimentology of the NNMR have been the focus of extensive research. Geomorphic features of the NNMR have been mapped using a consistent bathymetric grid of Australia's EEZ and relevant scientific literature (Heap and Harris, in press). A summary of the key geological and oceanographic events as well as prominent sedimentary and geomorphic features within the NNMR are provided below.

3.2.2. Tectonic History

The NNMR is an active continental margin with a complex tectonic history that is reflected in the geomorphology and geology of the region. The NNMR is a submerged section of the Australian continental crust which is bound to the north by an extinct accreting plate margin (Jongsma, 1974; Nicol, 1970). Tectonic rises and depressions located in the NNMR, such as the Van Diemen Rise, are attributed to the collision of the Australian platform with Papua New Guinea and Indonesia (Jongsma, 1974). Major geological provinces within the NNMR include the Arafura Basin and Goulburn Graben. The Arafura Basin is filled with Cambrian to Permo-Triassic (~542 – 251 Ma) sediment that is overlain by the middle Jurassic (~175 Ma) sediments of the Money Shoal Basin (Bradshaw et al., 1990). The Arafura Basin consists of northern and southern platforms that are separated by a northwest inclining Goulburn Graben situated on the southern margin (Heap et al., 2004; Moore, 1995) (Fig. 3.15). The Goulburn Graben is filled with marine clastics and carbonates which vary in age from the lower Cambrian to the Permian (~542 – 299 Ma) (Moore, 1995).

The major tectonic events of the NNMR summarised in chronological order are as follows:

- Permian-Triassic (~251 Ma) boundary – Continental break-up of northern Gondwana occurred (Pigram and Panggabean, 1981). This is recorded in a rift-drift sequence that extends along the northern margin of Australia (Brown, 1980; Pigram and Panggabean, 1981; Pigram and Panggabean, 1984).
- Middle Jurassic (~175 Ma) – A period of seafloor spreading and crustal uplift of northern Australia occurred (Audley-Charles et al., 1988; Pigram and Panggabean, 1984).
- Late Jurassic (~165 – 161 Ma) – The northern margin of Australia faced a seaway that linked the Indian and Pacific Oceans (Pigram and Panggabean, 1984).
- Cretaceous to Palaeogene (~145.5 – 23 Ma) – A period of profound subsidence occurred that exposed the islands of the Outer Band Arc (Audley-Charles et al., 1988).
- Cainozoic (~65.6 Ma – present) – Tectonic collision occurred, resulting in major strike and slip movements that are reflected in the bed forms of the northern margin (Audley-Charles et al., 1988).

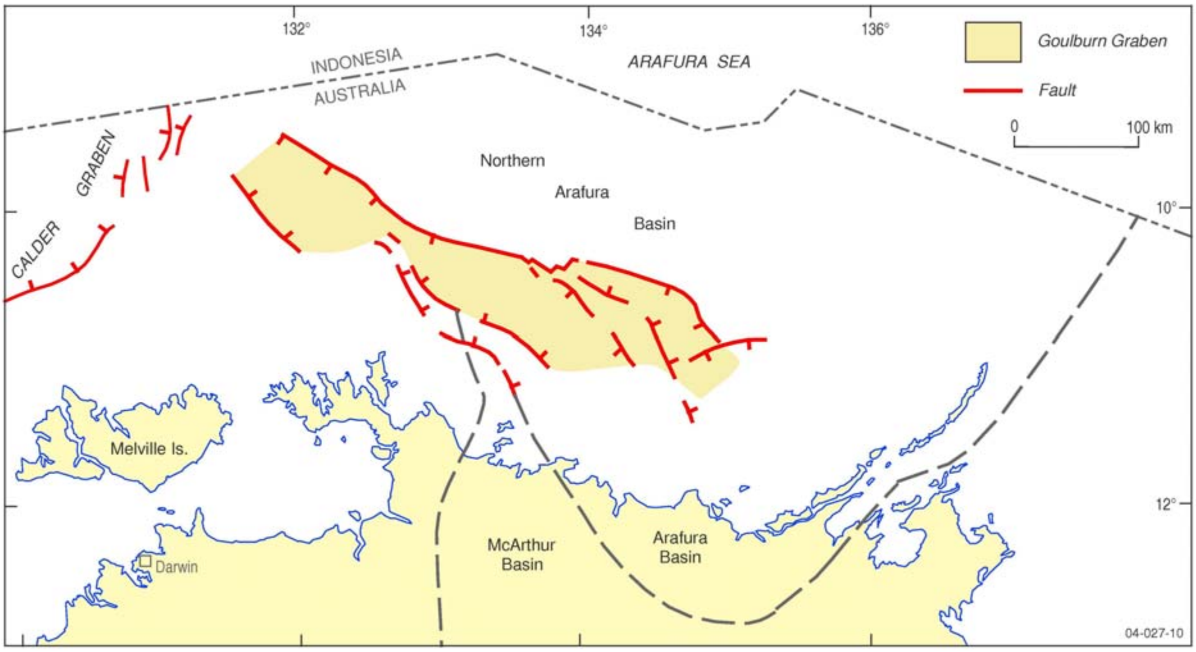


Figure 3.14. The geological setting of the Arafura Shelf, including the Arafura Basin and Goulburn Graben (from Moore, 1995).

3.2.3. Oceanography

The NNMR is a high energy oceanographic environment dominated by macro-tides, tropical cyclones and seasonal reversals of ocean currents. Tidal regimes follow semidiurnal and diurnal patterns, and generally attain more than 4 m. The tidal range is between 5.5 m - 7.9 m at Darwin and from 2 m - 4 m east of Darwin (Harris, 1994; Harris et al., 1991; Porter-Smith et al., 2004). Sea surface temperatures range from 25 - 29°C and average 27°C (Morrison and Delaney, 1996).

Circulation of the NNMR is influenced by the South Equatorial Current (SEC) and the Indonesian Throughflow (ITF) (Harris et al., 1991; Morrison and Delaney, 1996). Seasonal reversals of current flow occur in response to seasonal monsoons experienced in the region (Cresswell, 1992; Cresswell et al., 1993; Gupta, 2006). From April to November the SEC causes surface currents to flow westwards at a maximum mean rate of 0.5 ms^{-1} (Australian Pilot Volume V, 1992). This causes upwelling on the outer shelf and slope and increases productivity (Rochford, 1966). During the monsoonal season from December to March, current flow is weaker and unidirectional (Harris et al., 1991).

The oceanography of the NNMR influences the transport and deposition of seabed sediments. Inner shelf sediments are transported offshore by strong tides (Lees, 1992) that resuspend sediment into the water column (Morrison and Delaney, 1996). Outer shelf and slope sediments are transported by tropical cyclones that occur from November to March (Lourensz, 1981; Morrison and Delaney, 1996; Porter-Smith et al., 2004). These cyclones create strong winds and promote water movement that contribute to the erosion and deposition of fine-grained seabed sediments over large distances (Gagan, 1990; Harris, 1995).

3.2.4. Late Quaternary Evolution

The present day morphology of the NNMR is largely a result of low sea level erosional processes that occurred throughout the late Quaternary (Jongsma, 1974). During the LGM at ~18 ka BP, the shoreline of the Arafura and Sahul Shelf was 110 – 130 m below present position; and the shelves, including the Van Diemen Rise, were emergent and covered with arid woodland and dry sclerophyll vegetation (van Andel and Veevers, 1967; van der Kaars, 1991). By 15 ka BP – 13 ka BP, sea level had risen to ~55 m below its present position and mangroves and salt marsh occupied a large area of a low lying coastal plain (Lavering, 1994; van der Kaars, 1991). At about 9 ka BP, sea level rose to 15 m below present and stabilised at ~6 ka BP, bringing the shoreline to within ± 1-2 m of its present position (Lavering, 1994; van Andel and Veevers, 1967; van der Kaars, 1991).

Various geomorphic features, including terraces and palaeochannels, occur within the NNMR that reflect late Quaternary sea level fluctuations and the palaeoenvironment of the region. Several notches, steps, terraces, and scarps line the outer shelf and upper slope of the Arafura and Sahul Shelves. These occur at water depths of 122 m, 134 m, 147 m, 154 m, 163 m, 174 m, 181 m, and 225 m and record erosional processes probably associated with Pleistocene sea level fluctuations (Jongsma, 1974). A relict submarine valley system that acted as a passage for fluvial runoff during periods of low sea level extends from the Arafura Sill to the Arafura Depression within the NNMR (Harris et al., 1991). When sea level stabilised at ~6 ka BP the delivery of terrigenous sediment to the shelf decreased and the palaeochannels of this fluvial system were in-filled with marine dominated material (Grosjean et al., 2007).

Throughout the late Quaternary the NNMR was the site of limited coral reef growth (Napier, 1991). Relict reefs are located on the outer shelf/slope and on the sides of drainage channels, but they are less abundant than those of the NWMR (Harris et al., 1991). Reefs in the NNMR are sparsely distributed and probably grew in areas of local upwelling from the Timor Sea, flourishing through periods of high sea level and subjected to erosion during sea level lowstands (Heap et al., 2004).

3.2.5. Geomorphology

The NNMR comprises a complex geomorphology, which includes prominent features such as the Arafura Depression, Arafura Shelf, Bonaparte Depression, Flinders-Evans Shoals, Malita Shelf Valley, Parry Shoal, Sahul Shelf, and the Van Diemen Rise (Fig. 3.16 & Table 3.2.). Unassigned continental shelf covers the majority of the region, and this is intersected by a series of channels, terraces and ridges. The geomorphology of the NNMR is complex and represented by 12 of the 21 geomorphic features identified within Australia's EEZ (Heap and Harris, in press). These include: shelf (56.45% of total area within the NNMR), slope (3.54%), banks/shoals (5.46%), deeps/holes/valley (3.92%), basin (11.71%), reef (0.28%), canyon (1.13%), ridge (0.12%), pinnacle (0.23%), apron/fan (1.35%), terrace (15.65%), and tidal sand wave/sandbank (0.17%).

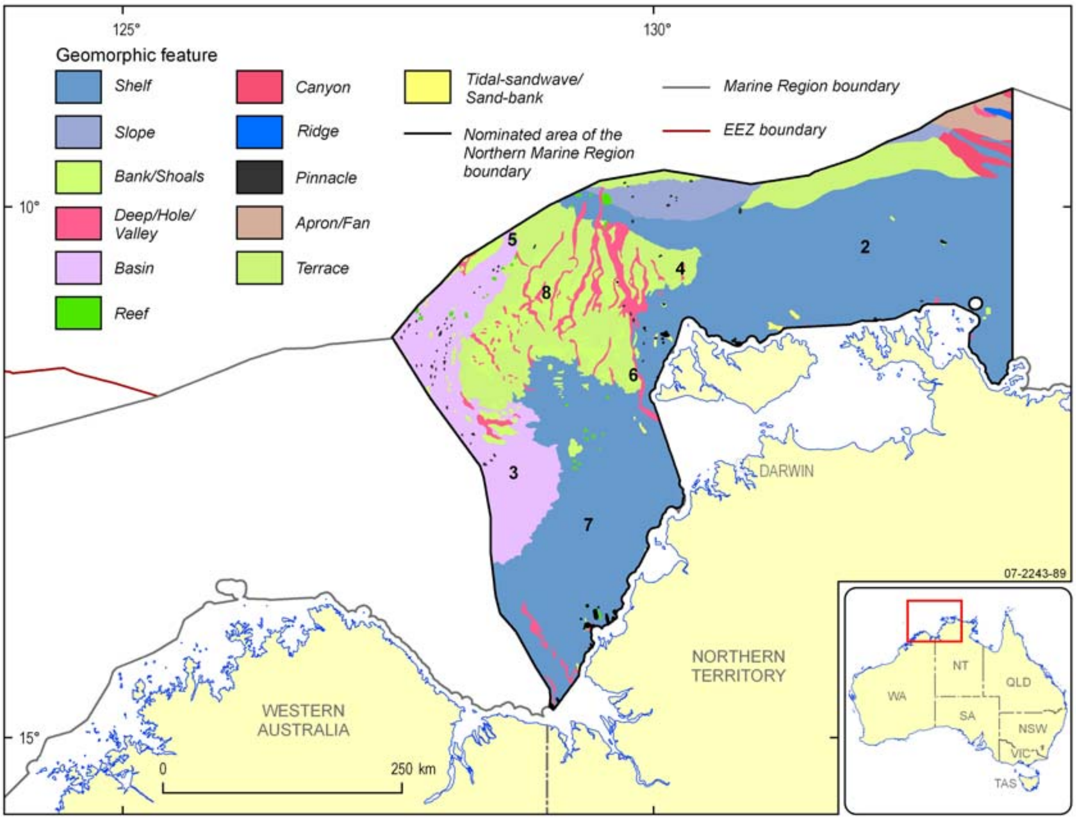


Figure 3.15. The geomorphic features of the NNMR as identified by Heap and Harris (in press). For key place names see Table 3.2.

Table 3.2. Place names and associated references for geomorphic features displayed in Figure 3.2.

No.	Geomorphic Feature	Feature Type	References
1	Arafura Depression	Valley (6)	Jongsma (1974)
2	Arafura Shelf	Shelf (1)	Carrigy & Fairbridge (1954)
3	Bonaparte Depression	Valley (6)	Lees (1992); van Andel & Veevers (1967)
4	Flinders-Evans Shoals	Bank (5)	van Andel & Veevers (1967)
5	Malita Shelf Valley	Valley (6)	van Andel & Veevers (1967); Lees (1992)
6	Parry Shoal	Shoal (5)	van Andel & Veevers (1967)
7	Sahul Shelf	Shelf (1)	Fairbridge (1953); van Andel & Veevers (1967)
8	Van Diemen Rise	Bank (5)	van Andel & Veevers (1967)

Continental shelf within the NNMR is separated into two portions, namely the Sahul and the Arafura Shelf. The Arafura Shelf covers an area of ~630,000 km^2 (Nicol, 1970) and is bound to the west by the Sahul Rise, to the north by the Arafura Depression and to the south by the Wessel Rise. The Sahul Shelf covers a total area of 415,000 km^2 (Carrigy and Fairbridge, 1954) of which 35,410 km^2 lies within the NNMR. The shelf extends from the Sahul Rise in the east to Cape Leveque in the NWMR.

The geomorphology of the Sahul Shelf is complex and consists of a series of rises, depressions, banks, terraces and channels (van Andel and Veevers, 1967). A series of submerged carbonate banks are located along the shelf edge and are separated from one another by narrow sinuous channels of up to 150 km in depth (Harris et al., 2003). Banks are interpreted by Lavering (1994) to be drowned carbonate platforms that were unable to keep pace with rising sea level during the Holocene. The banks are generally <10 km^2 in area with flat tops and developed both as terraces and benches and contain steep slopes of up to 33°, with an average of 20° (van Andel and Veevers, 1967).

The Arafura Shelf is the northernmost extension of Australia's continental shelf and is a broad and gentle seaward sloping plain of up to 350 km in width. Water depths on the Arafura Shelf range from 30 – 190 m, with the shelf edge situated in water depths of 120 – 180 m (Jongsma, 1974). The present day geomorphology of the shelf is largely the result of low sea level erosional processes that occurred throughout the Late Quaternary (Jongsma, 1974) (see section 3.2.4). The central and southern sections of the shelf are flat and mainly featureless except where the shelf approaches the Van Diemen Rise (Jongsma, 1974). The Van Diemen Rise is a complex topographic surface that separates the Arafura and Sahul Shelves. It consists of a series of algal banks that are separated from one another by narrow sinuous channels (Harris et al., 1991; Jongsma, 1974). To the east of the Van Diemen Rise lie the Parry and Flinders-Evans Shoals (van Andel and Veevers, 1967).

Two prominent depressions are located on the Arafura and Sahul Shelves, namely the Arafura and Bonaparte Depression. The Arafura Depression is located on the outer shelf/slope of the Arafura Shelf. A total of 5,000 km^2 of the depression is situated within the NNMR. The depression is a drowned fluvial system, composed of a series of ridges and valleys that existed throughout the LGM (Jongsma, 1974) (see section 3.2.4). A hummocky sedimentary fan occurs in the depression in water depths of 200-300 m, of which only the southernmost section is contained within the NNMR (Jongsma, 1974).

The Bonaparte Depression is a broad depression that occurs on the inner to middle Sahul Shelf that is bounded by the Londonderry, Sahul and Van Diemen Rises. The depression is a 45,000 km^2 basin that forms an epicontinental sea with a maximum water depth of 155 m (Lees, 1992). The eastern flank of the depression is relatively steep, the western flank relatively gentle, and the south merges into a broad featureless plain (van Andel and Veevers, 1967). The floor is relatively flat and punctuated by numerous pinnacles and subaqueous banks (Harris et al., 1991). The Malita Shelf Valley is located to the north of the Bonaparte Depression and connects the depression to the Timor Trough. The valley is a long, narrow, curved channel that is fringed by small, steep, carbonate banks (van Andel and Veevers, 1967).

3.2.6. Sedimentology

Seabed sediments of the Arafura and Sahul Shelves are predominantly composed of coarse-grained calcareous material that is mostly transported by strong tidal currents and seasonal cyclones (Jongsma, 1974; Porter-Smith et al., 2004; van Andel and Veevers, 1967). Terrigenous sediments reach the Sahul Shelf from large river systems that deliver 1.96 ± 106 T of sediment to the Bonaparte Gulf each year (Lees, 1992). Terrigenous sediments on the Arafura Shelf have originated from Arnhem Land rivers, the Gulf of Carpentaria and from reworking of shelf sediments during the last transgression (Grosjean et al., 2007). Sedimentation rates of the

Arafura Shelf since the LGM have remained at 2 m/1,000 years on the inner shelf and 0.1 m/1,000 years on the middle shelf (Jongsma, 1974).

The distribution of seabed sediments in the Joseph Bonaparte Gulf and contained within the Sahul Shelf reflect the present-day oceanographic condition and display a distinct seaward fining pattern (Lees, 1992). Sediments are predominantly carbonate sands with extensive outer shelf foraminiferal facies and algal-foraminiferal banks (van Andel and Veevers, 1967). The transportation and reworking of relict carbonate material masks the significant terrigenous component of sediments delivered to the Gulf, resulting in the deposition of a lobe of mixed carbonate and terrigenous facies that define the path of bed-load transport (Lees, 1992). As tidal velocities decrease with distance offshore the sandy gravel and gravelly sand on the inner shelf grades to sand on the middle shelf and then to silty sands and clayey sands on the outer shelf (Lees, 1992).

Seabed sediments of the Arafura Shelf contain carbonate contents that range from 8 – 100% (Jongsma, 1974) (Fig. 3.16). The carbonate content increases with distance from sources of terrigenous sediments, such as the shelf edge, where coarse sediments have a carbonate content of >50% (Jongsma, 1974). North of Melville and Bathurst Island, a zone of almost pure calcarenite exists comprising abundant foraminifera and mollusc shells (Jongsma, 1974). Lower carbonate contents occur on the middle shelf region due to the input of terrigenous sediment from the mainland (Jongsma, 1974).

The textural component of sediments from the Arafura Shelf is dominated by coarse-grained sands and silty-clays (Jongsma, 1974) (Fig. 3.17). The gravel content of the inner shelf is mostly of terrigenous origin and composed of ferruginous siltstone and sandstone fragments (Jongsma, 1974). Foraminifera, benthic molluscs, bryozoans, echinoids, pteropods, calcareous algae and coral also form constituents of sediments on the Arafura Shelf. Planktonic foraminifera are abundant on the shelf however they are rare or absent in near shore samples (Jongsma, 1974). The coarsest sediments are located on banks and shoals such as the Flinders-Evans Shoal and Parry Shoal (Lavering, 1994). Fine-grained pelagic sediments are located on the upper slope where sediment accumulation has remained un-interrupted during the last two million years (Jongsma, 1974).

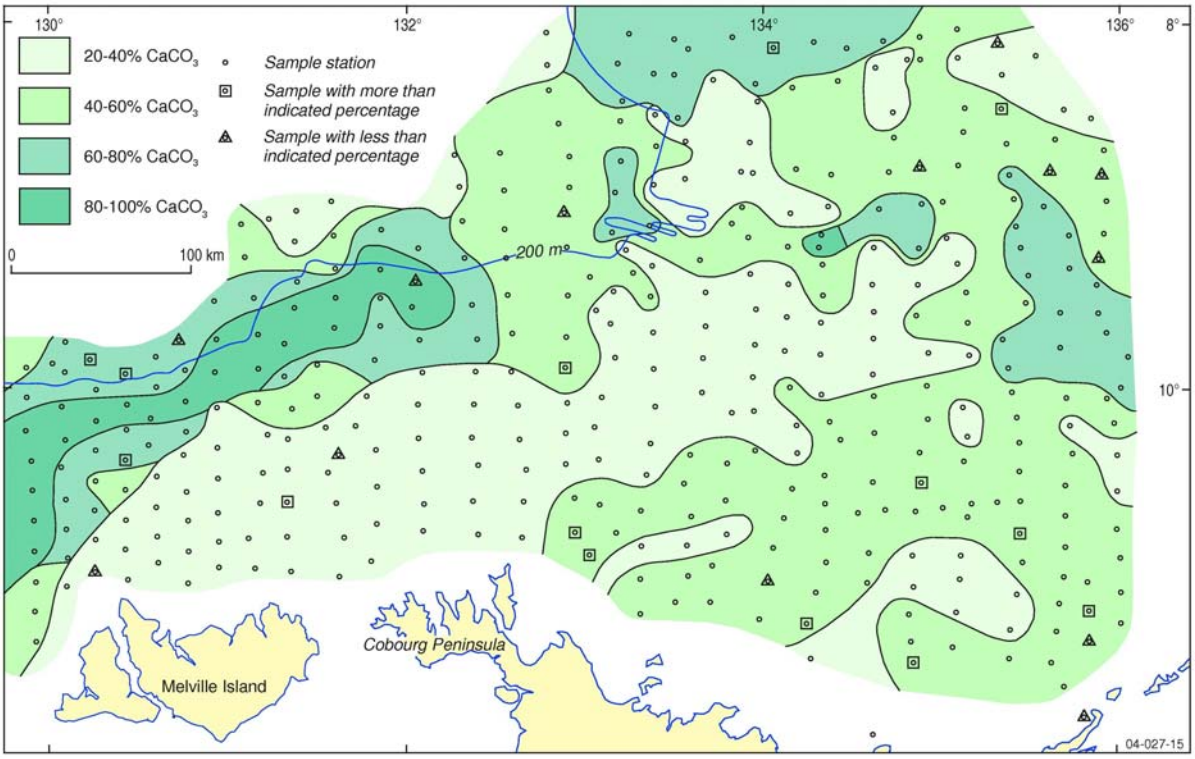


Figure 3.16. The distribution of calcium carbonate concentrations on the Arafura Shelf (redrawn from Jongsma, 1974).

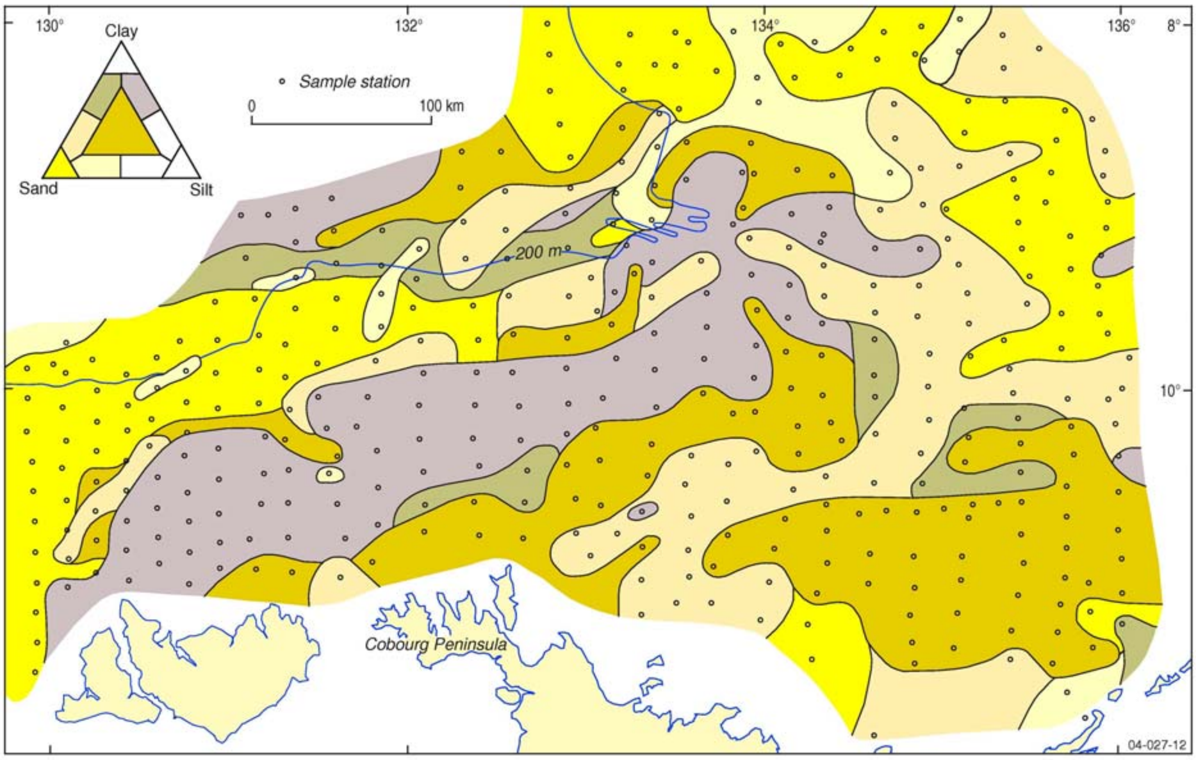


Figure 3.17. The distribution of surface sediments on the Arafura Shelf (redrawn from Jongsma, 1974).

4. Quantitative Description of the NWMR and NNMR

4.1. QUANTITATIVE DESCRIPTION OF THE NWMR

4.1.1. Geomorphology

Four geomorphic provinces occur in the NWMR (Fig. 4.1; Table 4.1). The slope makes up the largest area (61%, 647,600 km^2), followed by the shelf (28%, 304,200 km^2), abyssal plain/deep ocean floor (9%, 100,100 km^2), and rise (1%, 15,800 km^2). Relative to the rest of Australia's EEZ, the NWMR has a significantly larger percentage of slope and far lower percentage of abyssal plain/deep ocean floor. The NWMR contains approximately 16% of area of slope in the entire EEZ (Fig. 4.1; Table 4.1).

Of the 21 geomorphic features defined on the Australian margin, 19 are represented in the NWMR. Seamounts/guyots and escarpments are not represented (Fig. 4.2; Table 4.1).

Large areas of the shelf, slope and abyssal plain/deep ocean floor in the NWMR have not yet been identified in geomorphic features. These areas comprise 35% of the total NWMR area (shelf = 16%, slope = 16%, and abyssal plain/deep ocean floor = 3%). Geomorphic features covering significant areas of these provinces include terraces and plateaus on the shelf and slope which comprise 321,100 km^2 (30% of the area of these provinces in the NWMR). Knoll/abyssal hills/mountains/peaks and ridges are the only geomorphic features identified on the abyssal plain/deep ocean floor and cover 7,800 km^2 (<1%). No geomorphic features have been identified on the rise.

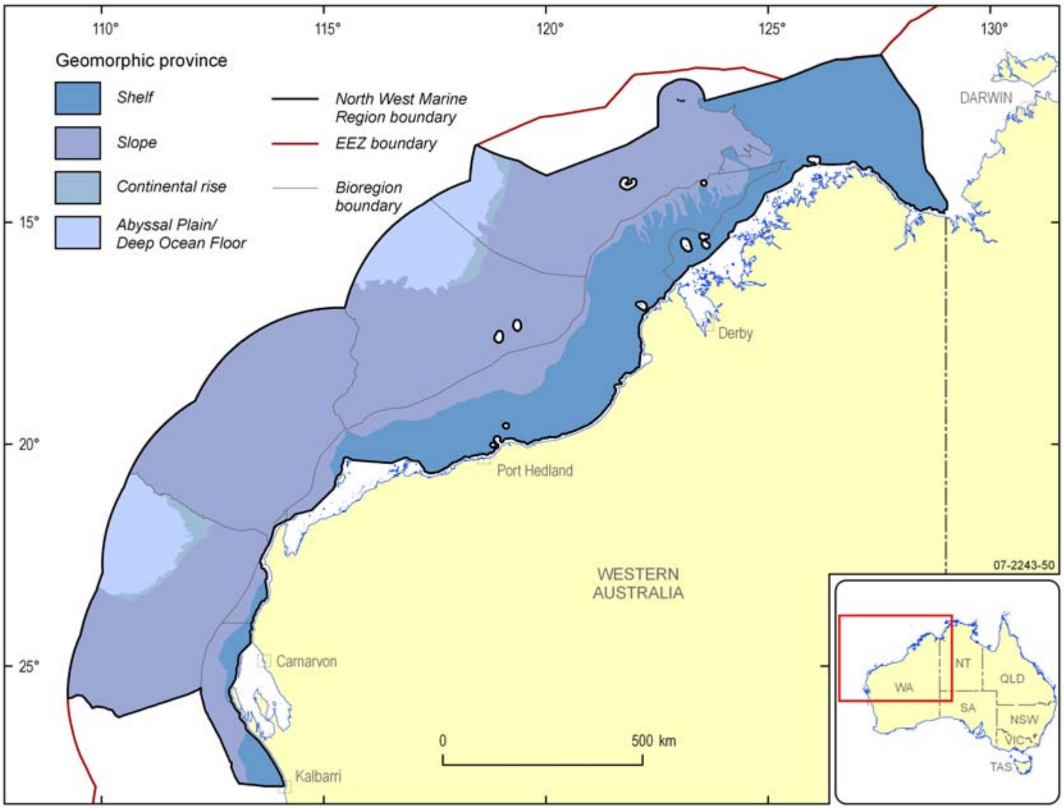
There are no geomorphic feature types that are unique to the NWMR, but some features that occur in the NWMR are rare elsewhere in the EEZ or the latitudes or water depths at which they occur in the NWMR. The NWMR contains a large proportion of the total area of several geomorphic features over the EEZ: Relative to the entire EEZ, the NWMR is particularly rich in banks/shoals, deeps/holes/valleys and terraces. Banks/shoals in the NWMR cover 29,100 km^2 or 58% of the total area of banks/shoals in the EEZ, followed by deeps/holes/valleys (93,300 km^2; 56%); and terraces (227,000 km^2; 39%) (Fig. 4.2; Table 4.1).

Table 4.1. Statistics of geomorphic provinces and features of the NWMR.

Feature	Area in NWMR	% Total NWMR Area	% EEZ Area	% Total area of feature in EEZ located in NWMR	Water Depth Range in NWMR (m)
Geomorphic Provinces					
Shelf	304,170	28.49	21.76	15.50	0 - 330
Slope	647,650	60.66	44.42	16.17	34 – 5,705
Rise	15,845	1.48	1.13	15.50	4,035 – 5,695
AP/DOF*	100,065	9.37	31.96	3.47	3,289 – 5,975
Geomorphic Features					

Shelf	134,115	12.56	13.79	10.78	0 - 200
Slope	310,580	29.09	15.23	22.61	21 – 5,700
Continental Rise	15,845	1.48	1.06	16.54	4,035 – 5,695
Abyssal Plain	98,720	9.25	27.34	4.00	3,375 – 5,975
Bank/Shoals	29,065	2.72	0.56	57.54	4 - 165
Deep/Hole/Valley	93,290	8.74	1.83	56.49	15 – 5,270
Trench/Trough	10,120	0.95	1.93	5.82	570 – 1,285
Basin	19,740	1.85	7.36	2.97	25 - 160
Reef	2,090	0.20	0.52	4.49	35 – 1,330
Canyon	10,790	1.01	1.18	10.10	95 – 5,705
Knoll/Abyssal Hils/Mountains/Peak	2,000	0.19	1.32	1.69	1,700 – 5,605
Ridge	5,800	0.54	1.25	5.20	115 – 5,180
Seamount/Guyot	0	0	1.11	0	-^
Pinnacle	680	0.06	0.06	13.24	5 - 295
Plateau	94,115	8.81	16.59	6.29	15 – 4,625
Saddle	7,990	0.75	1.62	5.45	150 – 4,300
Apron/Fan	735	0.07	0.13	6.29	5 - 460
Escarpment	0	0	0.23	0	-^
Sill	3,720	0.35	0.19	21.44	70 - 95
Terrace	226,975	21.26	6.43	39.16	10 – 4,995
Tidal Sandwave/Sand Bank	1,355	0.13	0.27	5.64	0 - 85
TOTAL	*1,067,725*				

* AP/DOF = Abyssal plain/deep ocean floor.
^ cell size too small to calculate bathymetry



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b)

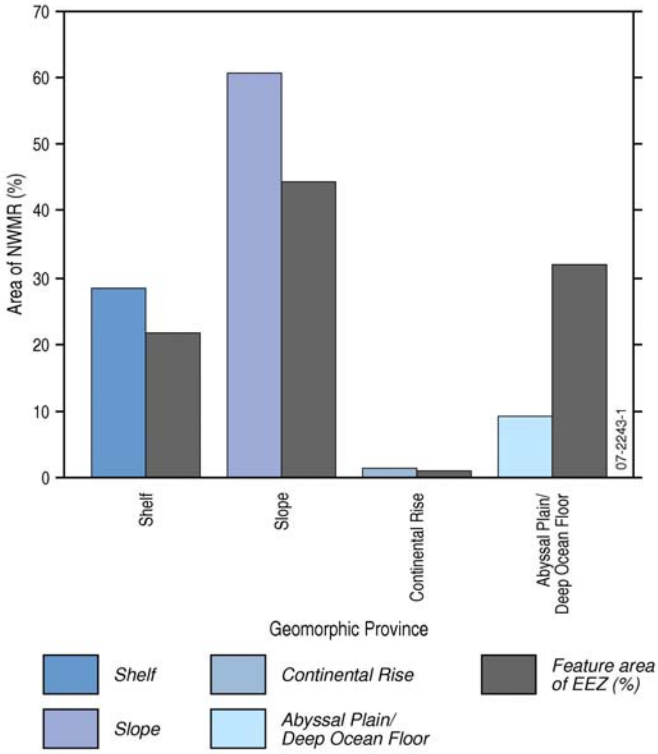
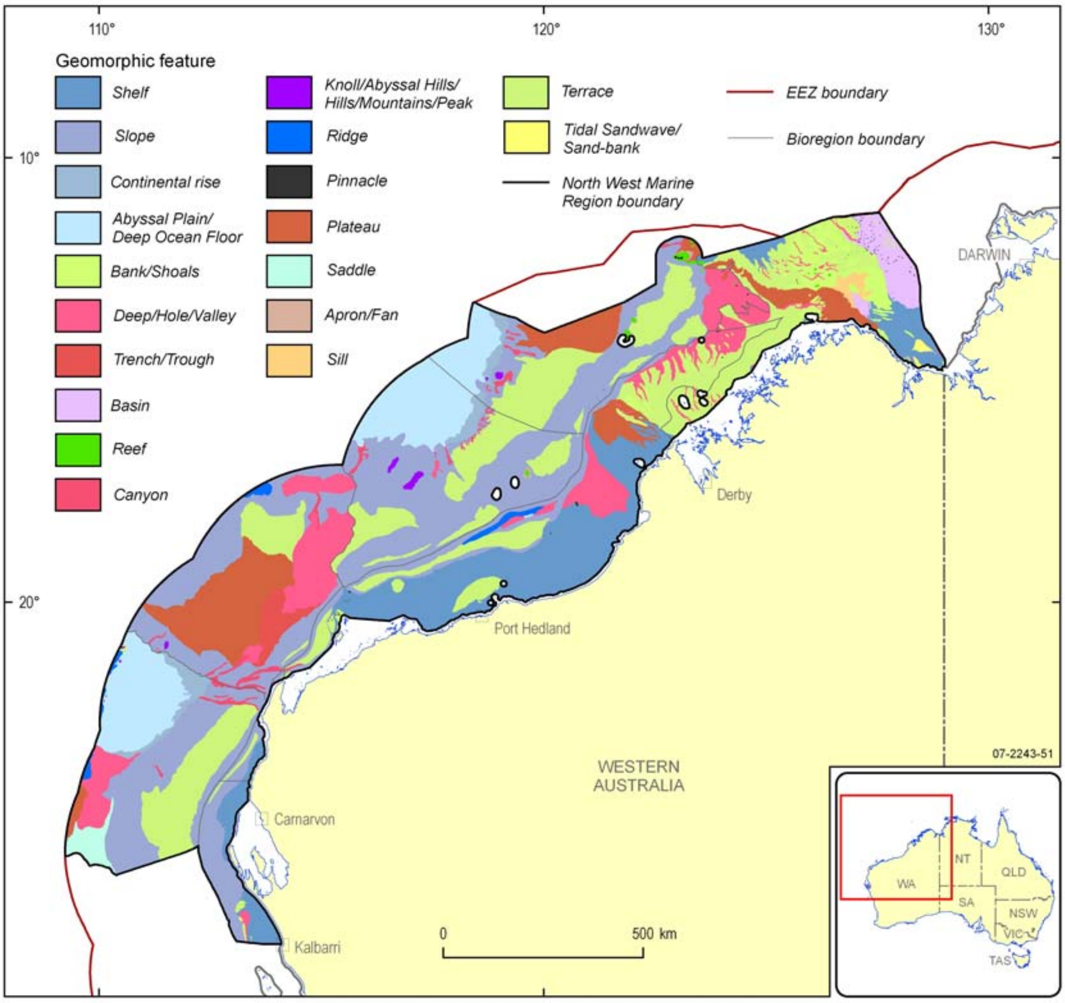


Figure 4.1. a) Geomorphology of the NWMR and b) percentage area of each geomorphic province within the NWMR and EEZ.


110°
120°
130°
10°
20°
Geomorphic feature
Shelf
Slope
Continental rise
Abyssal Plain/
Deep Ocean Floor
Bank/Shoals
Deep/Hole/Valley
Trench/Trough
Basin
Reef
Canyon
Knoll/Abyssal Hills/
Hills/Mountains/Peak
Ridge
Pinnacle
Plateau
Saddle
Apron/Fan
Sill
Terrace
Tidal Sandwave/
Sand-bank
North West Marine
Region boundary
EEZ boundary
Bioregion boundary
DARWIN
Derby
Port Hedland
WESTERN
AUSTRALIA
Carnarvon
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a)

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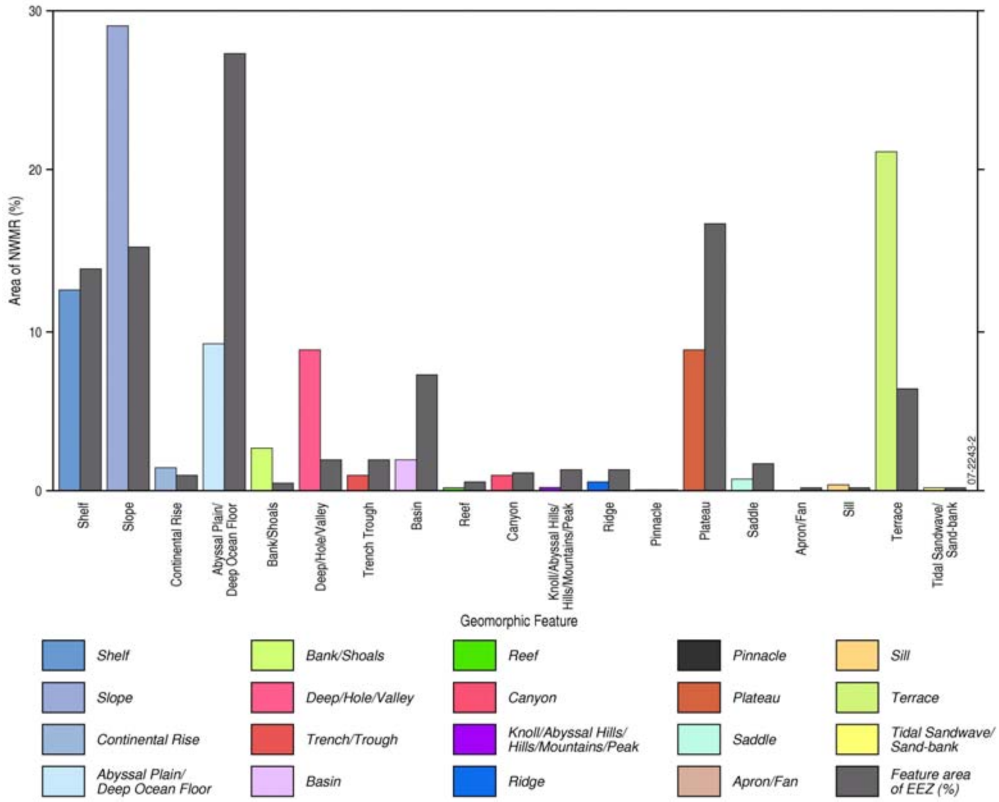


Figure 4.2. a) Geomorphology of the NWMR and b) percentage area of each geomorphic feature within the NWMR and EEZ.

4.1.2. Bathymetry

Water depths in the assessed area of the NWMR range from 0 – 5,980 m (Table 4.1; Figs. 4.3). The NWMR is relatively shallow, with >40% of the total area in water depths of <200 m and >50% in depths of <500 m. This reflects the broad shelf and slope that occurs along much of the northwestern Australian margin. Compared with the entire EEZ, the NWMR contains a relatively small area of deep water (>4,000 m). Water depths of >4,000 m comprise <15% of the NWMR area, or <5% of the total EEZ area (Fig. 4.3).

Basins, pinnacles and apron/fans in the NWMR have a limited depth range compared to the rest of the Australian margin, occurring only in water depths shallower than 500 m (Table 4.1). Elsewhere in the EEZ, these features occur in water depths from 0 to >5,000 m (Potter et al., 2006).

More than 70% of the total area of knoll/abyssal hills/hills/peaks in the NWMR occur at water depths of >4,000 m. Elsewhere in the EEZ, these features are most common at water depths of <1,500 m (see, Potter et al., 2006). Knoll/abyssal hills/hills/peaks in the NWMR comprise >70% of the total area of this feature across the EEZ in water depths of >4,000 m.

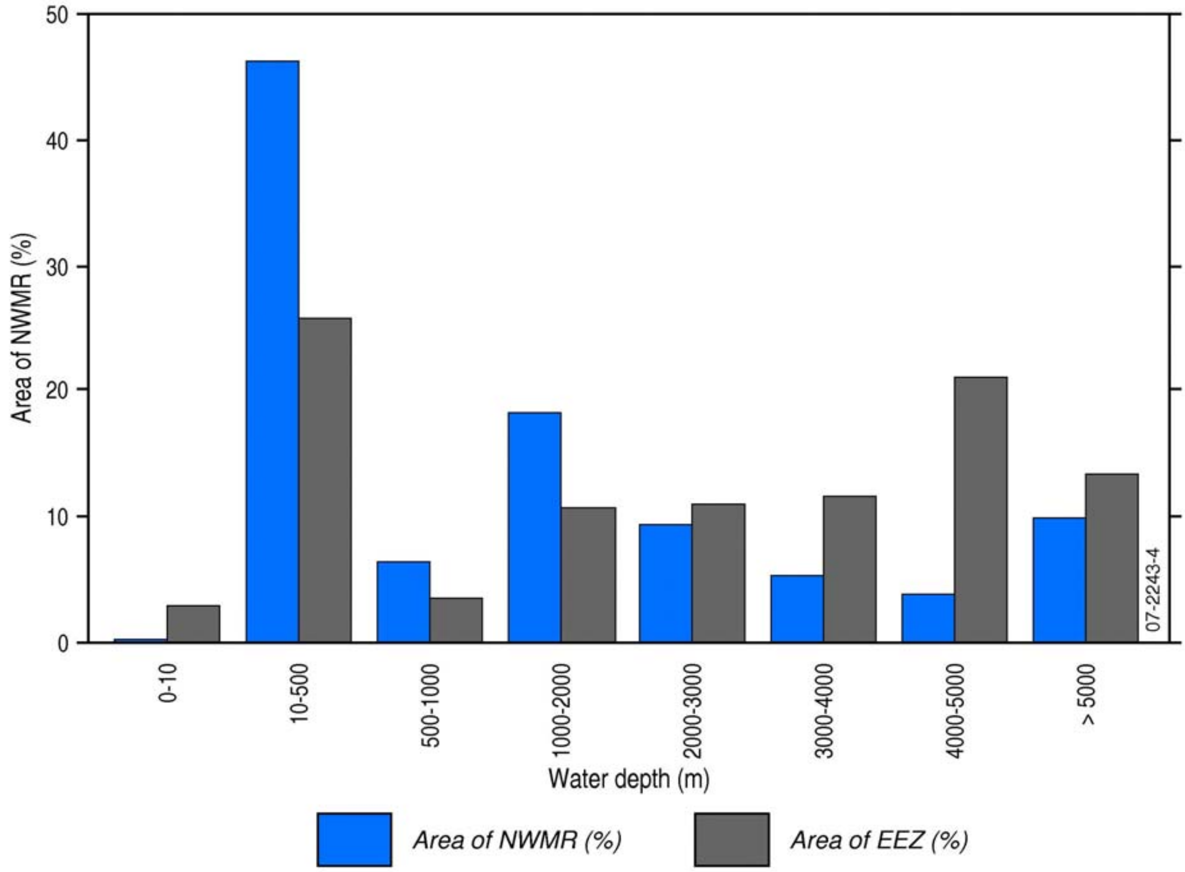


Figure 4.3. Distribution of water depths for the NWMR (grey bars) and EEZ (grey bars) expressed as percentages.

4.1.3. Sediment Data Coverage in the NWMR

4.1.3.1 Quantitative Textural and Compositional Data

Sample density varies significantly across the NWMR (Fig. 4.4 & Fig. 4.5). Sample density exceeds ten samples per 1,000 km² for more 35% of the total area of the NWMR and exceeds 50 samples per 1,000 km² for >3%. Sample density does not attain one sample per 1,000 km² for approximately 20% of the NWMR area (Fig. 4.5). Samples are clustered as a result of collection on surveys of local areas or targeting specific seabed features. In general, sample coverage is most dense on the mid to outer shelf and the upper slope (Fig. 4.6). Samples are relatively sparse in deep water areas and on much of the inner shelf (Fig. 4.6 & 4.7).

A total of 449 samples (46% of samples in the NWMR) are from the shelf, resulting in an average sample density of approximately 1.5 samples per 1,000 km² (Fig. 4.7; Table 4.2). A total of 508 (52%) samples are from the slope, resulting in an average density of 0.8 samples per 1,000 km². Only 11 (<2%) samples occur on the rise and abyssal plain/deep ocean floor; however, as these provinces form a relatively small area of the NWMR (~115,900 km², <11%), this gives an average density of 0.1 samples per 1,000 km² (Fig. 4.7). Samples achieve adequate coverage to assess the sedimentology in 11 of the 19 geomorphic features present in the NWMR. No samples were collected from saddles. Less than three samples were collected from the rise, knoll/abyssal hills, aprons/fans, sills and tidal sand wave/sandbanks. Together, these features cover approximately 23,660 km² (<2%) of the NWMR (Table 4.1).

Average sample densities exceed 0.8 samples per 1,000 km² for all features, covering >100,000 km² or 10% of the NWMR. Of those features containing adequate samples for analysis, highest sample densities were achieved for pinnacles and ridges (~3 samples per 1,000 km²) and deeps/holes/valleys and aprons/fans (~1.4 samples per 1,000 km²). Low numbers of samples and/or spatial clustering of samples on some features mean that assays may not be representative of seabed properties for the entire feature across the NWMR. Low numbers of samples may significantly affect results for trench/trough, reefs, canyons and pinnacles. A total of eight samples occur on the abyssal plain/deep ocean floor in the NWMR. Clustering may significantly affect results for canyons, ridges, and terraces.

Despite targeted addition of data points, coverage remains poor (<1 sample per 1,000 km²) particularly for some areas of the inner shelf, the abyssal plain/deep ocean floor and rise. Addition of data improved coverage of deeps/holes/valleys and knoll/abyssal hills that occur in water depths >4,000 m (1 sample added to each)but was unable to achieve coverage of ridges, canyons and saddles occurring at these water depths in the NWMR.

It is important to note that average densities and areas given for these will vary depending on the scale (Marine region/province/feature) at which density is being assessed.

Table 4.2. Description of average density of samples per geomorphic province or feature.

PROVINCE/ # Feature	No. sample points	% NWMR Area	Average sample density (samples per 1,000 km²)
Geomorphic Province			
Shelf	449	28.49	1.48
Slope	508	60.66	0.78
Rise	1	1.48	0.06
Abyssal Plain/ Deep Ocean Floor	10 + 18 in deepwater outside EEZ	9.37	0.10
Geomorphic Province			1.70
Shelf (unassigned)	228	12.56	0.79
Slope (unassigned)	244	29.09	0.06
Continental rise (unassigned)	1	1.48	0.08
AP/DOF (unassigned)	8	9.25	1.31
Bank/Shoals	38	2.72	1.40
Deep/Hole/Valley	131	8.74	0.30
Trench/Trough	3	0.95	1.32
Basin	26	1.85	1.43
Reef	3	0.20	0.37
Canyon	4	1.01	1.00
Knoll/Abyssal Hills/Mountains/Peak	2	0.19	3.10
Ridge	18	0.54	2.95
Pinnacle	2	0.06	0.46
Plateau	43	8.81	0.00
Apron/Fan	0	0.75	1.36

Sill	1	0.07	0.27
Terrace	1	0.35	0.93
Tidal Sandwave/Sand bank	211	21.26	2.95

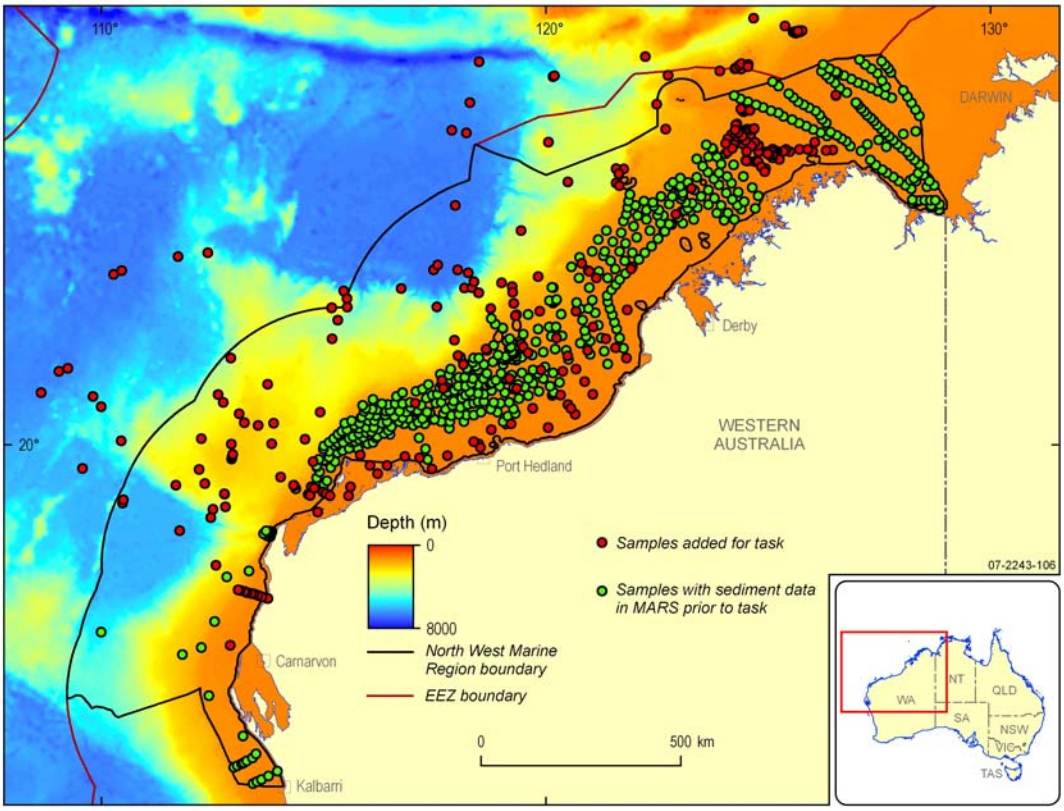
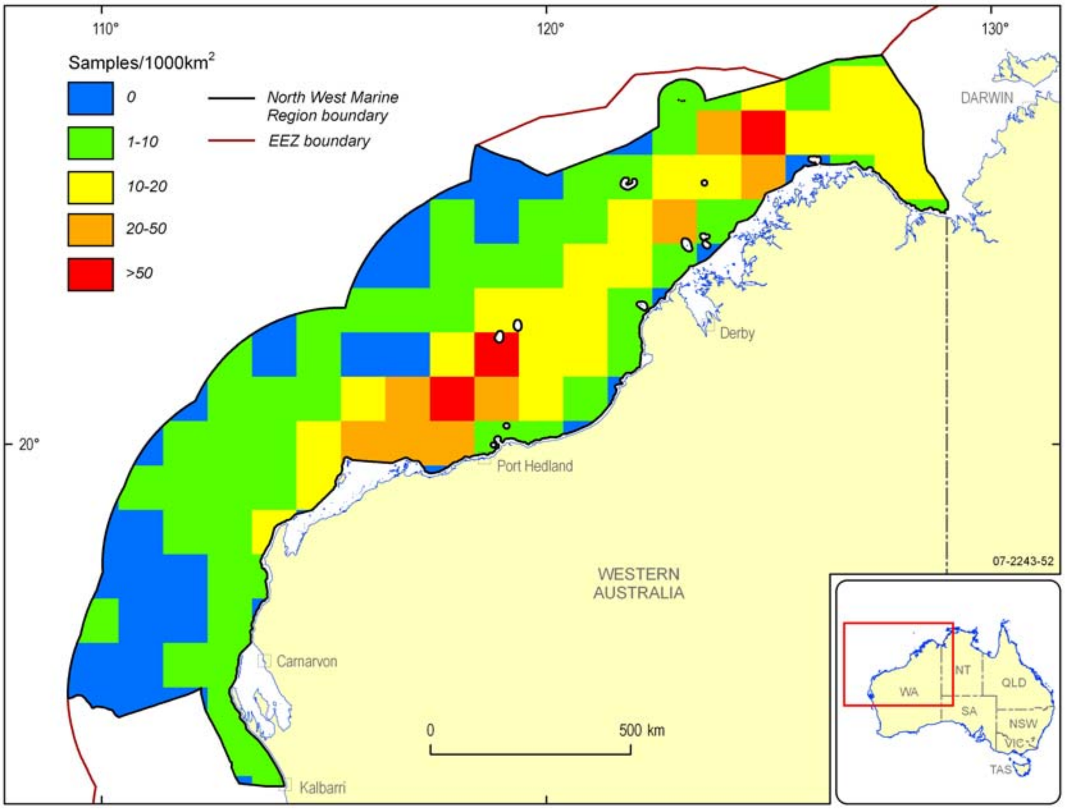


Figure 4.4. Location of all quantitative textural and compositional sample points for the NWMR in relation to bathymetry.



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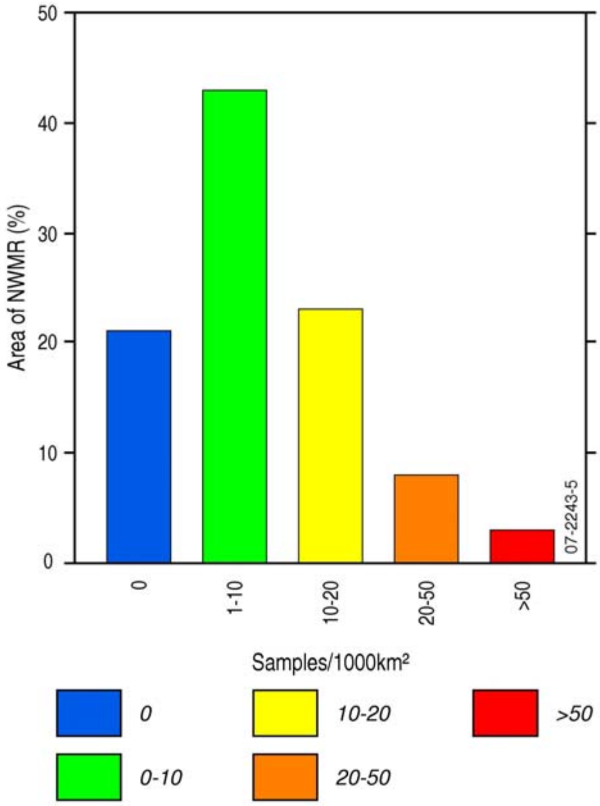


Figure 4.5. a) Sample density distribution across the NWMR, and b) Frequency distribution of sample density.

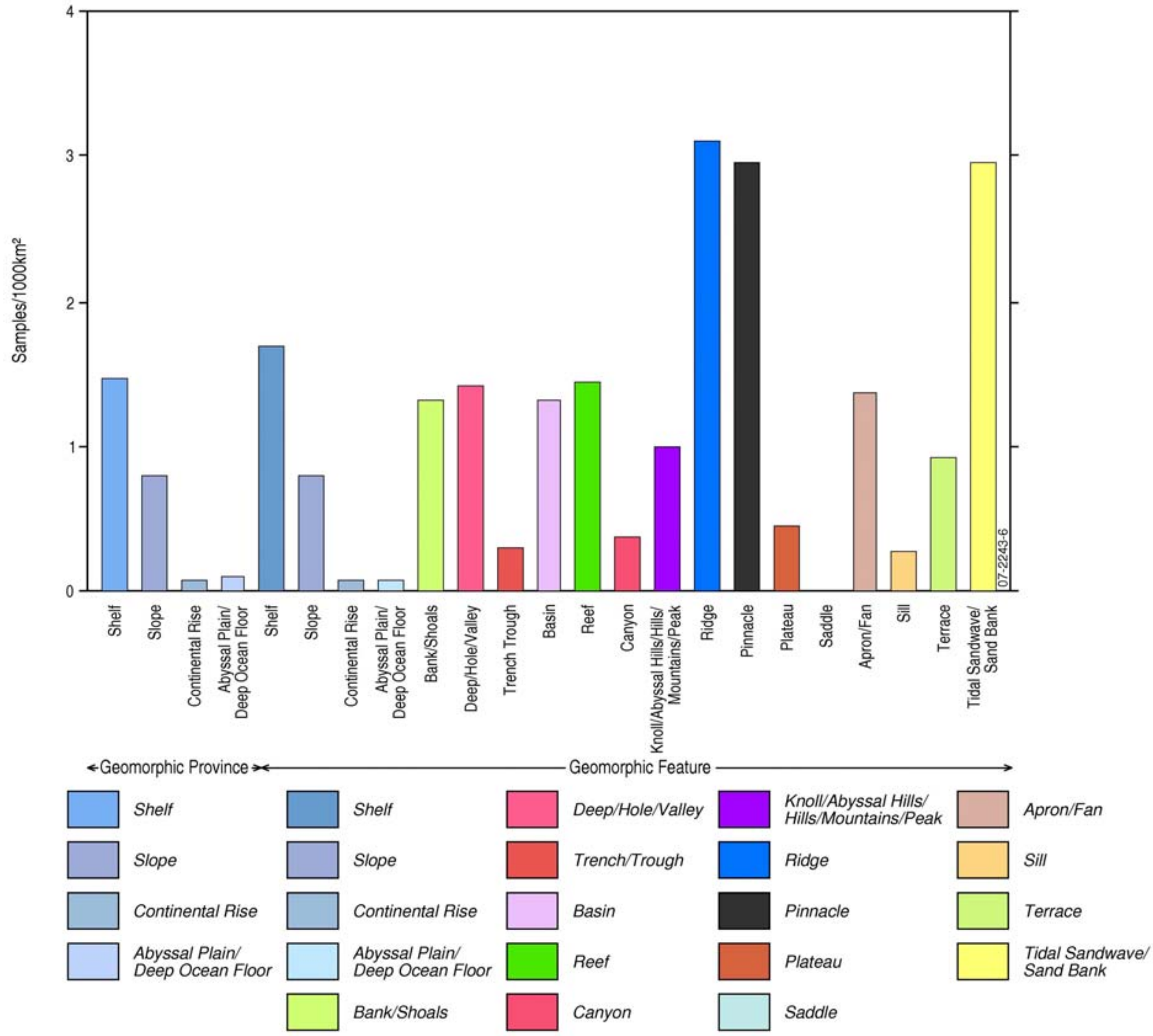
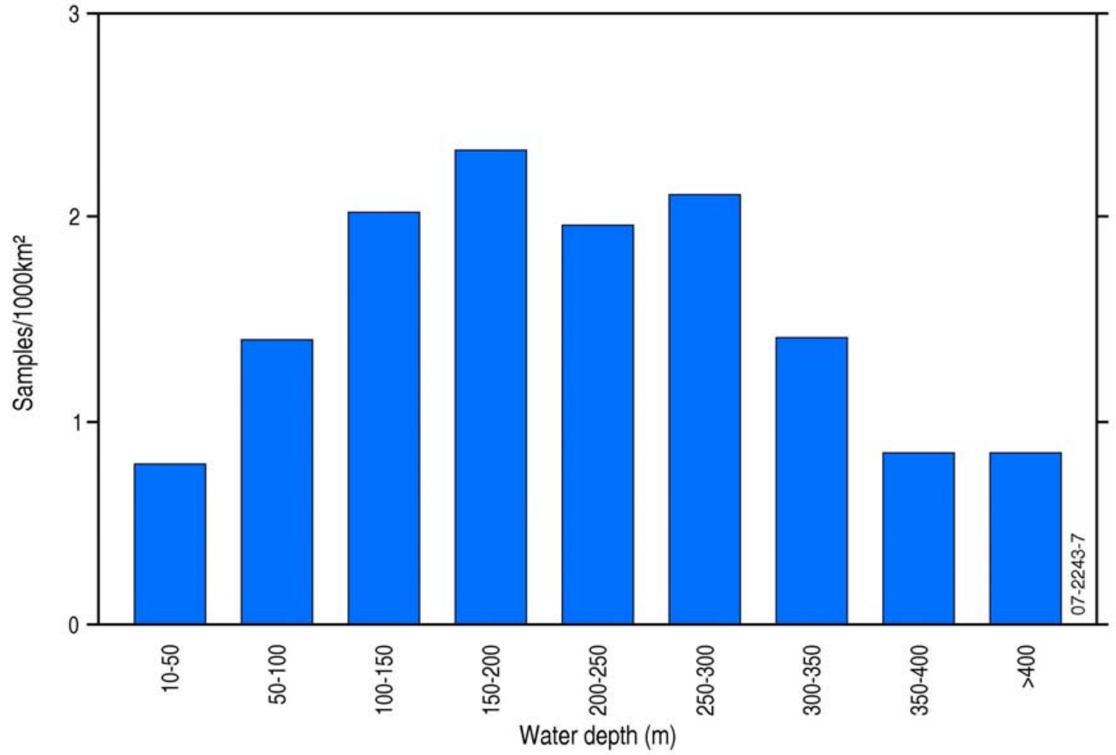


Figure 4.6. Sample density of geomorphic provinces and features in the NWMR (y axis shows average density measured as samples per 1,000 km²).

a)



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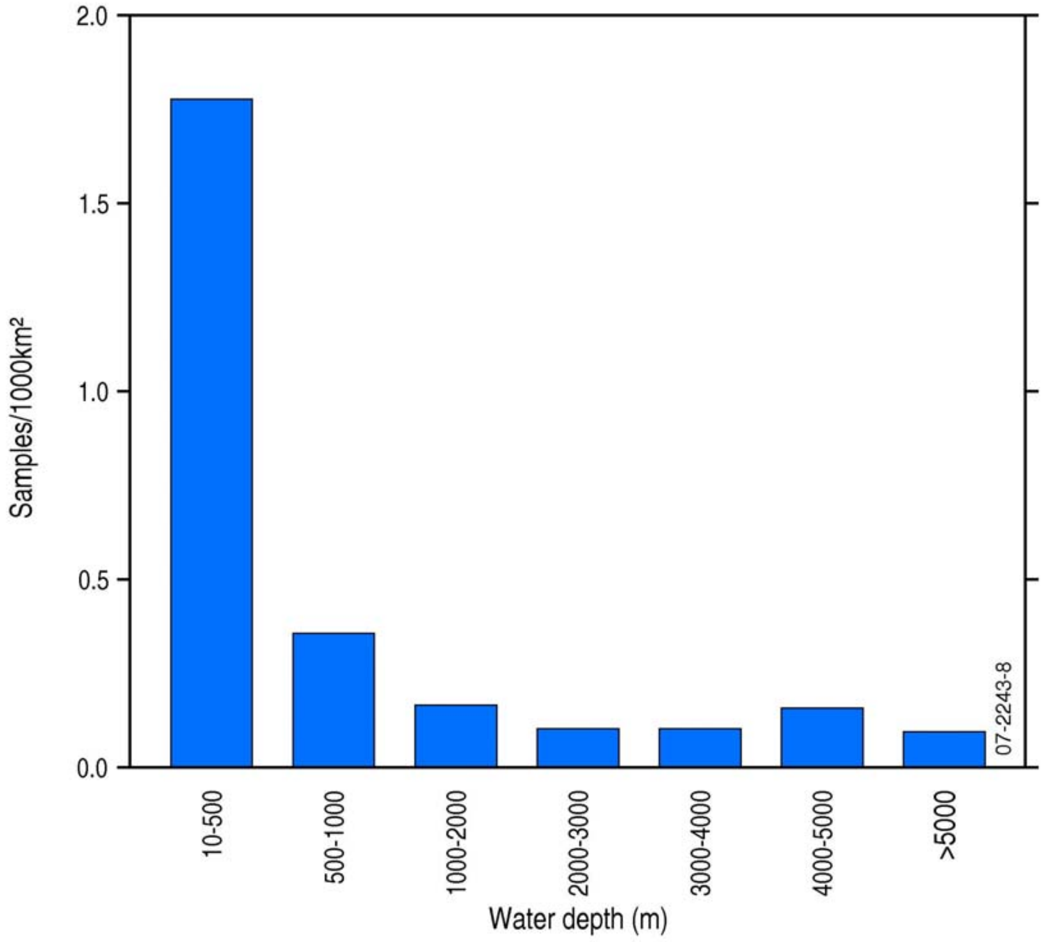


Figure 4.7. Sample density for water depths for a) depths <500 m in the NWMR, and b) for all provinces in the NWMR (y axis shows average density measured as samples per 1,000 km²).

4.1.4. Quantitative regional sediment distribution in the NWMR

4.1.4.1. Overview of Distribution and Properties

Sample assays indicate that the seabed in the NWMR is characterised by a range of sediment types (Fig. 4.8). Sand is the dominant size fraction with approximately 627 samples (65%) containing >50% sand. A total of 43 samples (4%) contained <10% sand (Fig. 4.11b). Sand is the dominant size fraction in samples located on the shelf and upper slope except in the Bonaparte Depression and on the Londonderry Rise where mud comprises >50% of sediment at approximately 80 (30%) sites sampled (Figs. 4.10 & 4.11).

A total of 222 samples (23%) contained >50% mud and 384 (40%) samples contained <10% mud (Fig. 4.10b). Mud is the dominant size fraction on the slope, rise and abyssal plain/deep ocean floor (Figs. 4.10a & 4.14). Samples containing <10% mud generally occur on the shelf and upper slope.

Gravel is detected in 640 (66%) samples but is the dominant size fraction in only 47 (<1%) samples. Gravel forms a minor component (<10%) in approximately 617 samples (64%) (Fig. 4.12b). Gravel occurs most frequently on the shelf and upper slope and is generally absent from deep water areas (Fig. 4.12a, 4.14). The abundance and distribution of sediment containing gravel is likely to be underrepresented in the data due to sparse sample coverage of areas of the NWMR closest to the coast.

Carbonate is the dominant constituent of the sediment with 568 (69%) samples composed of >80% carbonate (Figs. 4.9 & 4.13b). Less than 28 samples (<4%) contain <10% carbonate. Carbonate content generally decreases with increasing water depth, with more than 50% of samples on the shelf and upper slope containing >90% carbonate (Fig. 4.13a). Carbonate contents on the lower slope generally vary between 20 and 90%. Exceptions occur in the Bonaparte Depression and on the shelf around Shark Bay. In the Bonaparte Depression, shelf sediment contains <80% carbonate and frequently <20% (Fig. 4.13a).

All size fractions are dominated by carbonate grains (Fig. 4.9). Carbonate mud contents attain >50% for 231 (28%) samples. Carbonate mud content generally shows variation over large distances, with assays of similar contents clustered even at a regional scale. As >1 g of mud is required to perform this analysis, assays are mainly from samples off the shelf and may not to be representative of carbonate contents of mud across the entire planning region.

Carbonate sand is the dominant constituent of sediment in the NWMR with contents attaining >50% in 408 (50%) samples. The carbonate content of sand varies spatially, although lower concentrations are generally more frequently observed in close proximity to the coast. Exceptions to this trend occur in the Bonaparte Depression and on the Londonderry Rise where carbonate sand contents are <60% and frequently <20%. Carbonate contents of sand in this region are generally <60% and frequently <20%.

Gravel is entirely composed of carbonate grains in 270 (33%) samples. Carbonate is exceeded by other constituents in only three (<1%) samples. These occur on the slope and represent the deepest-water occurrences of gravel detected in the NWMR. It is not possible to observe spatial trends in carbonate contents of gravel as volumes of gravel necessary to complete this analysis were only collected from the shelf and upper slope.

Sediment assays were interpolated using the methods described in Chapter 2 to give an estimate of regional distribution of sediment properties in the NWMR. Interpolated grainsize data achieves coverage of approximately 735,500 km (69%) of the total NWMR. Uneven distribution of data points in the region means that interpolated sediment data covers 335,200 (85%) of the shelf, 707,550 km^2 (62%) of the slope and 119,500 km^2 (32%) of the rise/ abyssal plain/deep ocean floor. Interpolated bulk carbonate data and folk classification cover similar areas of each province.

The interpolated maps give an interpretation of possible regional distribution of sediment properties (Fig. 4.14). Areas with the highest sand (40-100% sand) and lowest mud (<20% mud) content are located on the mid to upper shelf (Figs 4.10a & 4.11a). Mud content shows a significant increase with water depth, and the highest contents are located within the lower slope, abyssal plain/deep ocean floor, and to the north of the Bonaparte Archipelago. The NWMR is predominantly composed of sediment with a low gravel content (<20%) (Figs. 4.12a & 4.12b).

The highest calcium carbonate contents occur in sediment located within the shallow reaches of Shark Bay and along the Rowley Shelf (Fig. 4.13a). Sediment in the Joseph Bonaparte Gulf is characterised by frequently low carbonate contents. Carbonate content generally decreases with water depth, and the lowest values are found on the lower slope and abyssal plain/deep ocean floor.

Areas of highest gravel composition are found within the Joseph Bonaparte Gulf and offshore of Broome within the northern extent of the Northwest Shelf Province (Fig 4.12a & 4.14). From the Folk Classification (Fig 4.15a), gravely sand (gS) with smaller quantities of sandy gravel (sG) dominate the shelf area, and muddy sand (mS) and gravely muddy sand ((g)mS) dominate the lower slope (Fig 4.15a). The distribution of muddy sand (mS), mud (M), and sandy mud (sM) increases with water depth, and these sediment types are most common with the abyssal plain/deep ocean floor.

The textural composition of seabed sediment grades from sand-dominated to mud-dominated with increasing water depth. A notable change in the sedimentology occurs offshore of the Joseph Bonaparte Gulf towards the extent of the Timor Sea. In this region sediment show a decrease in calcium carbonate composition and an increase in mud content. This change is best observed in the Folk Classification where an increase in the deposition of gravelly muddy sand (gmS) is observed (Fig 4.15a).

It should be noted that interpolated sediment maps and graphs showing sediment composition include only sample points with weight % data. Due to low sample volumes or different analysis methods in the past, mean grainsize is the only information available for many samples. For this reason, sample numbers stated in the text may differ from numbers of points displayed on maps and graphs.

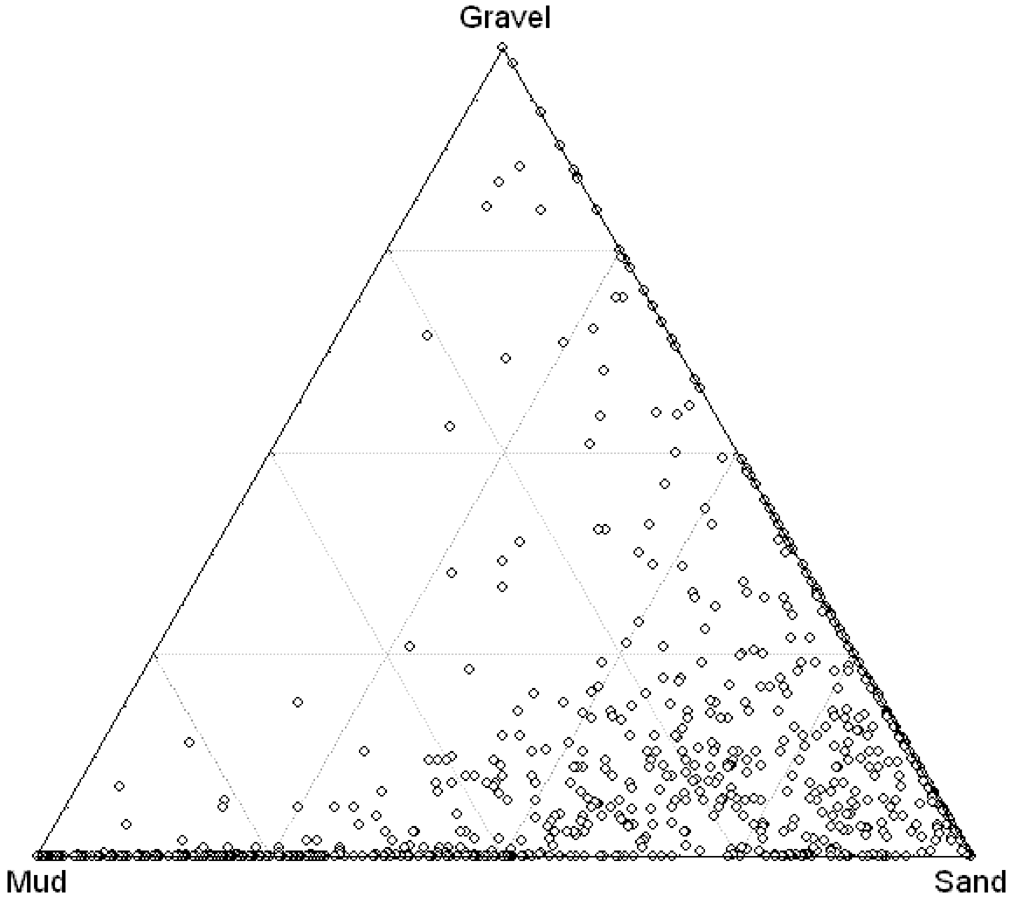
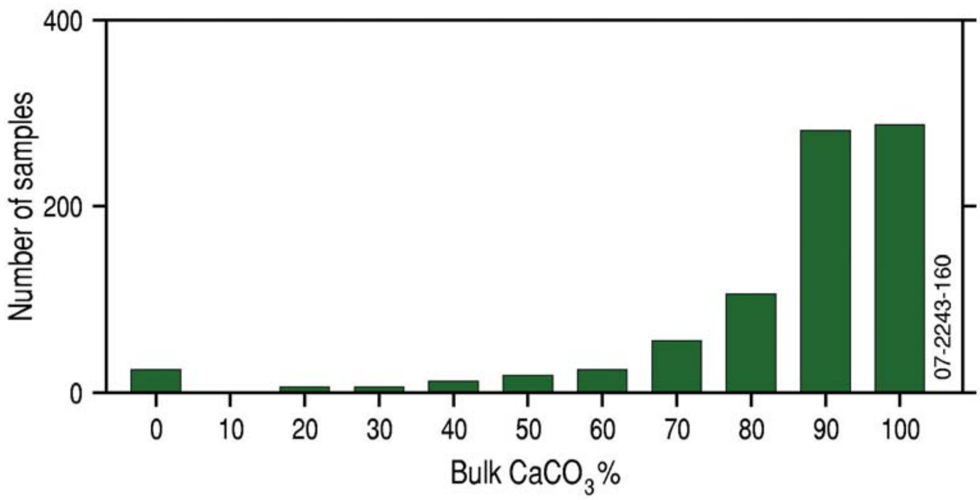
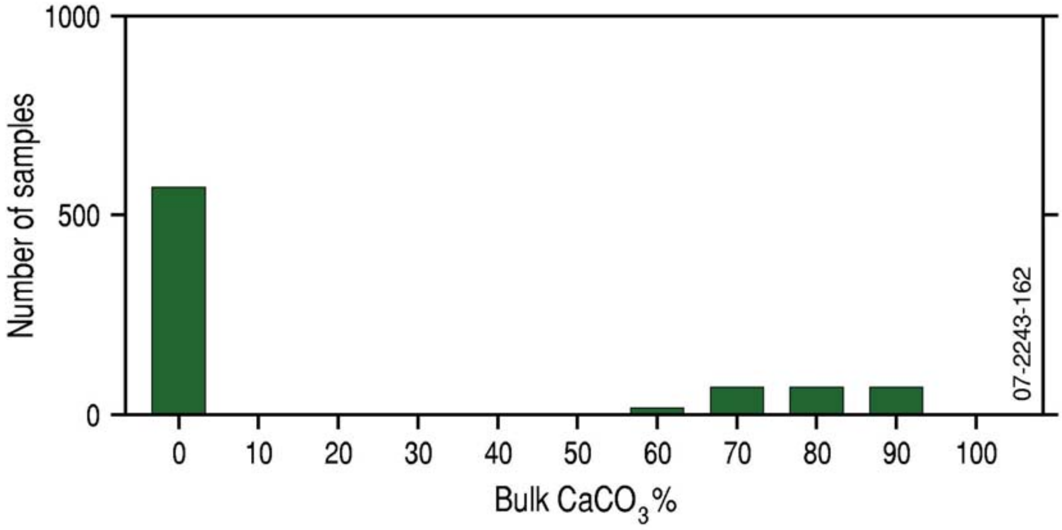


Figure 4.8. Textural composition (mud:sand:gravel ratio) of individual sediment samples within the NWMR.

a)



b)



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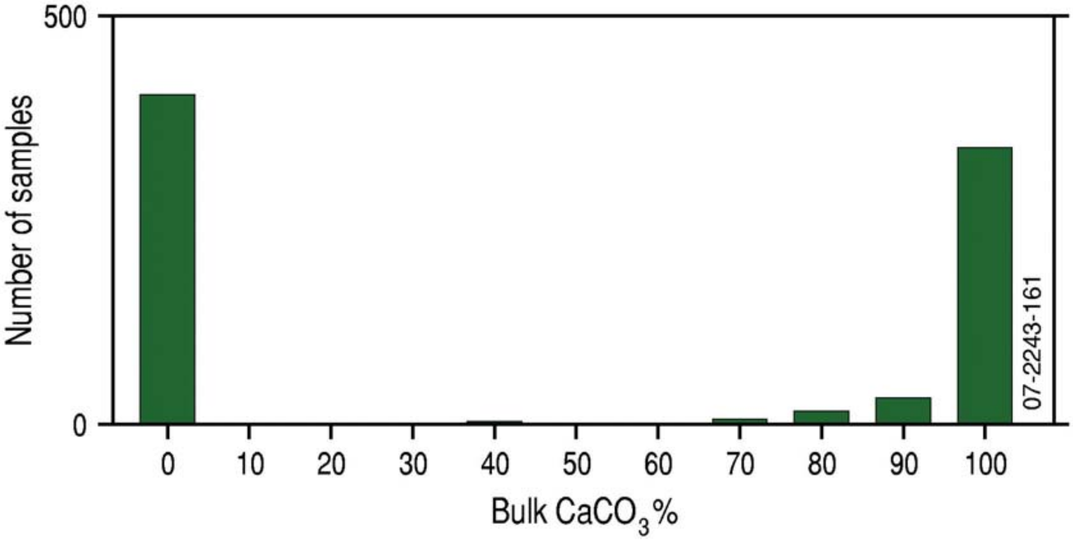

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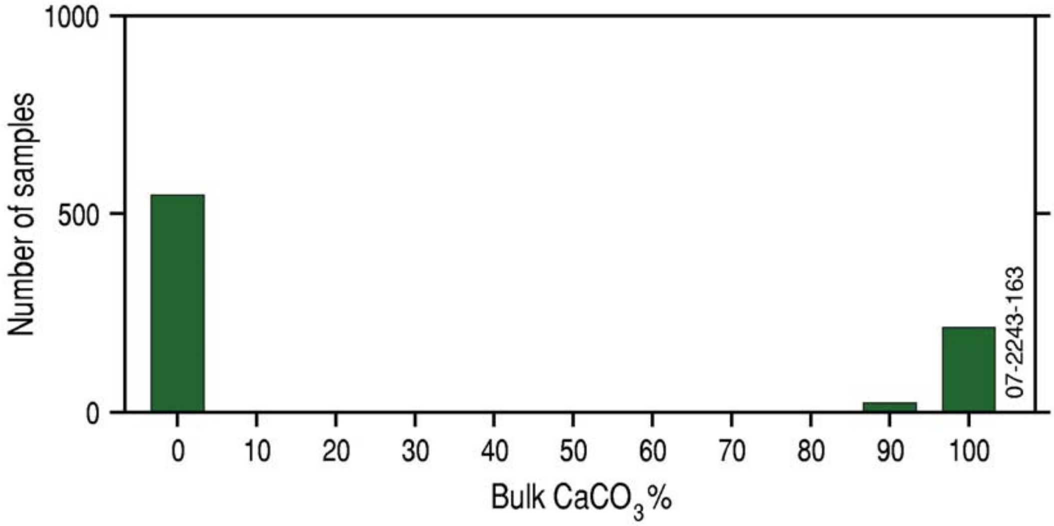
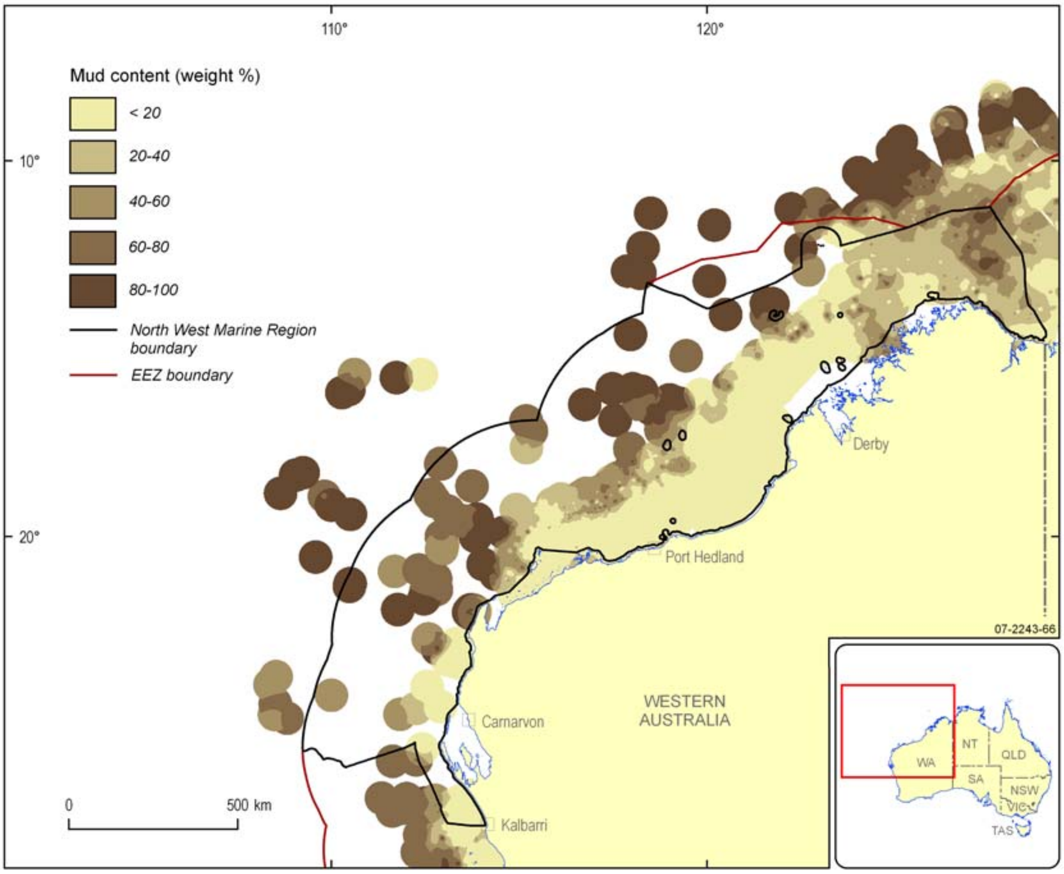


Figure 4.9. a) the bulk carbonate content, and carbonate content of b) mud, c) sand, d)gravel (d) sediments in the NWMR.



a)

b)

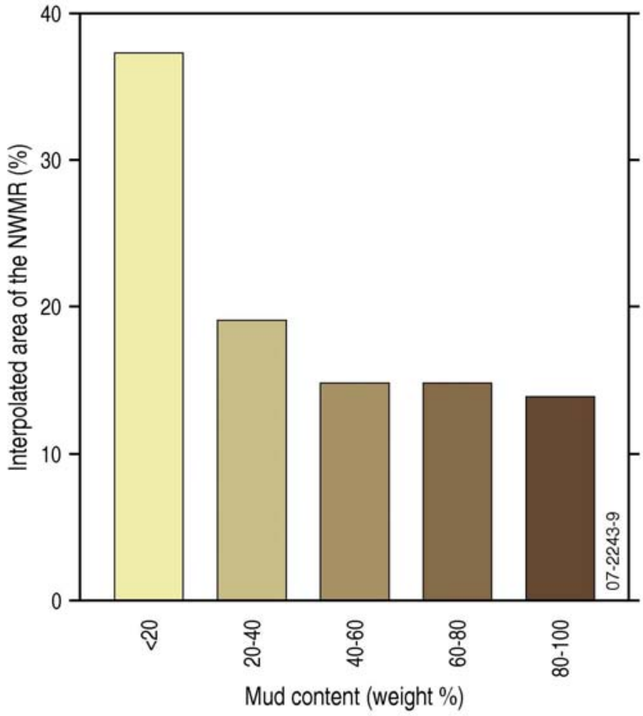
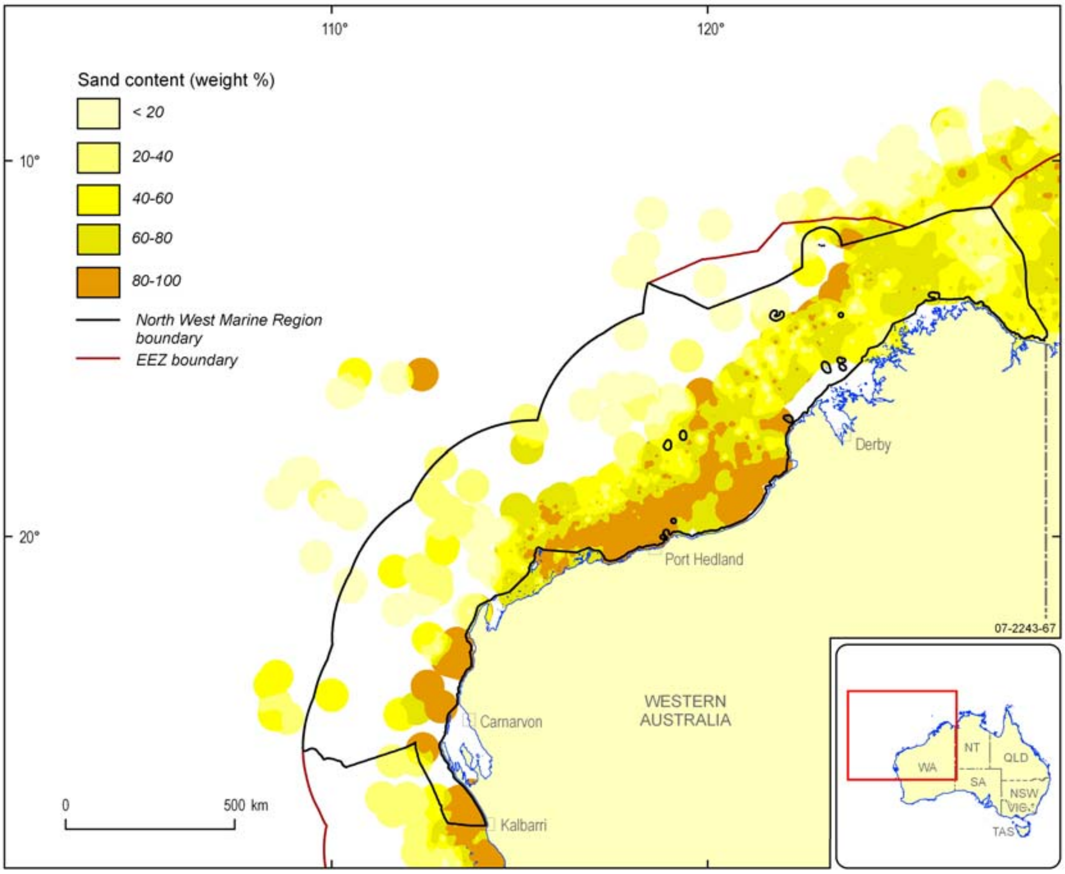


Figure 4.10. a) Mud distribution in the NWMR and b) the area covered by each mud class expressed as % of the interpolated area of the NWMR.



a)
b)

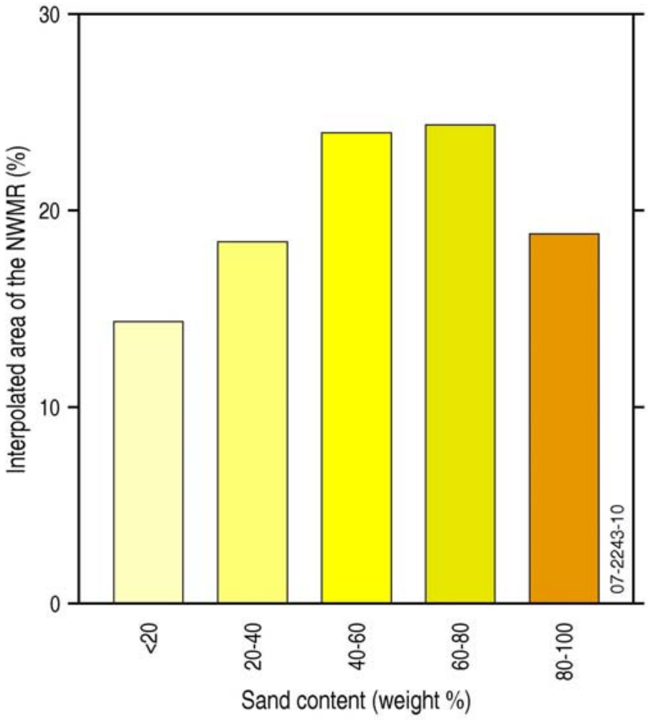
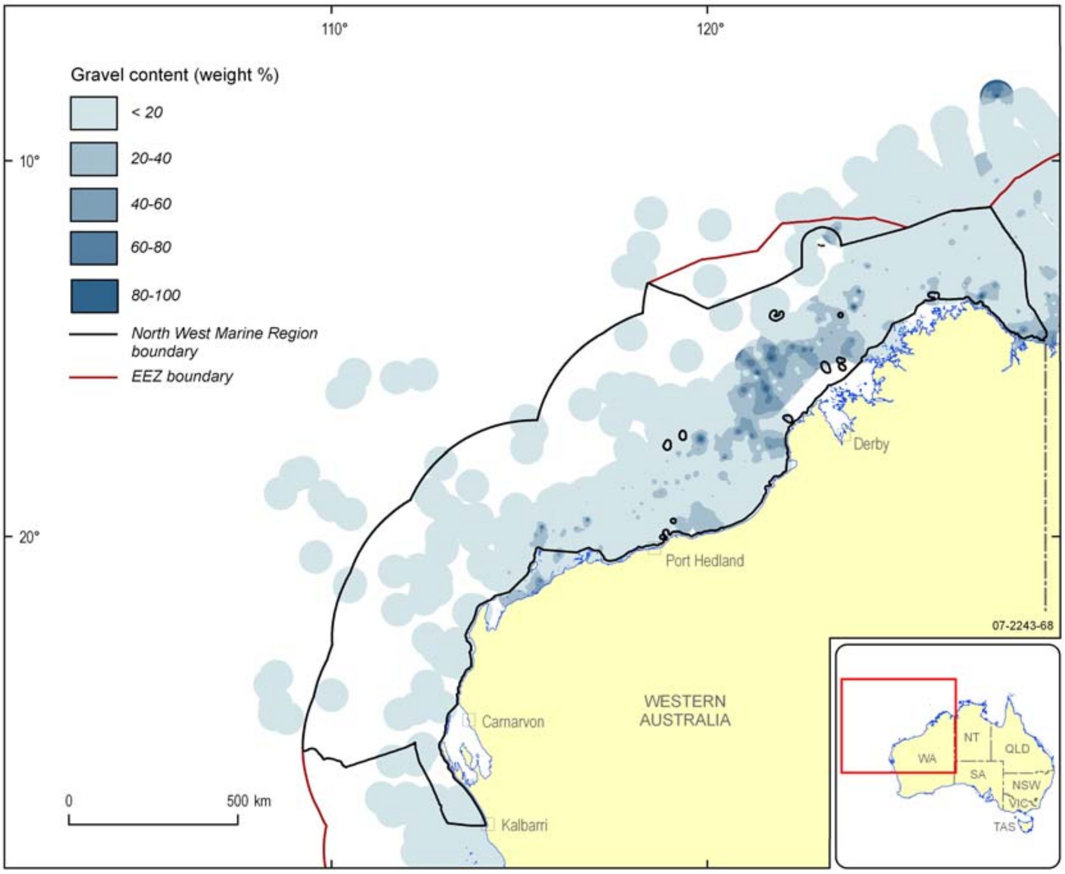


Figure 4.11. a) Sand distribution in the NWMR and b) the area covered by each sand class expressed as % of the interpolated area of the NWMR.



a)

b)

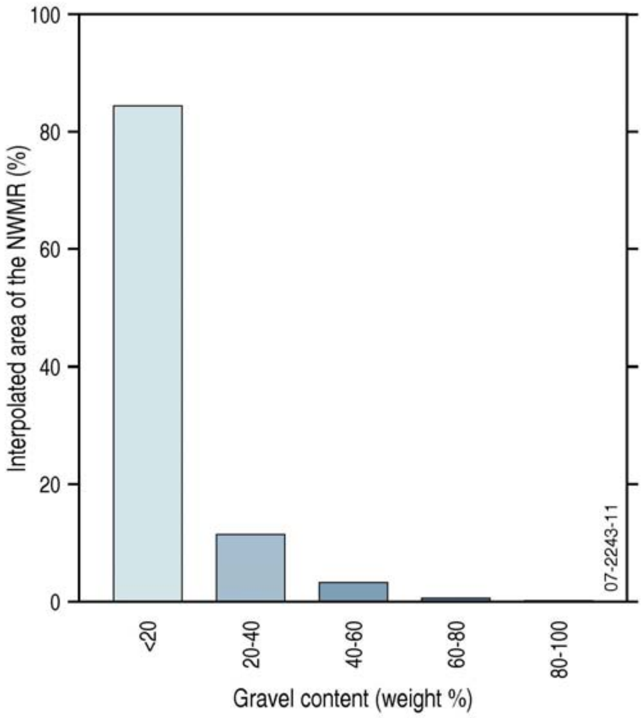
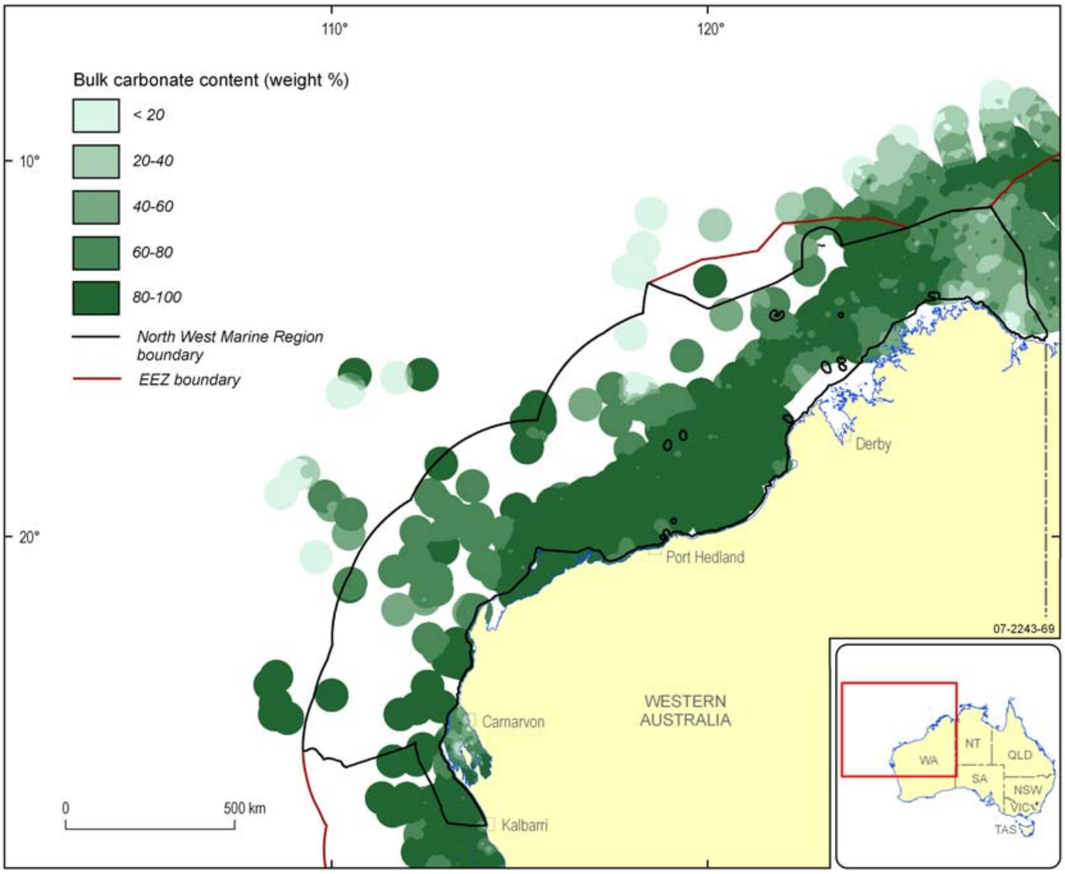


Figure 4.12. a) Gravel distribution in the NWMR and b) the area covered by each gravel class expressed as % of the interpolated area of the NWMR.



a)

b)

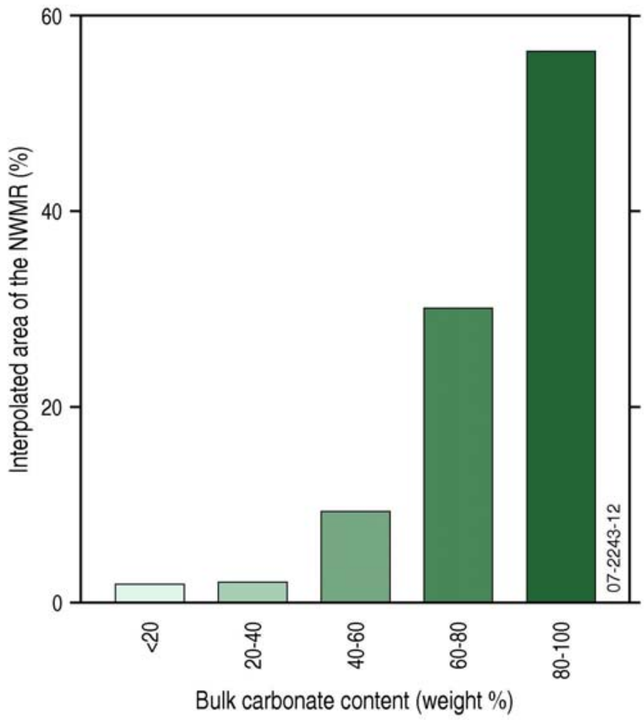


Figure 4.13. a) Carbonate content distribution in the NWMR and b) the area covered by each carbonate content class expressed as % of the interpolated area of the NWMR.

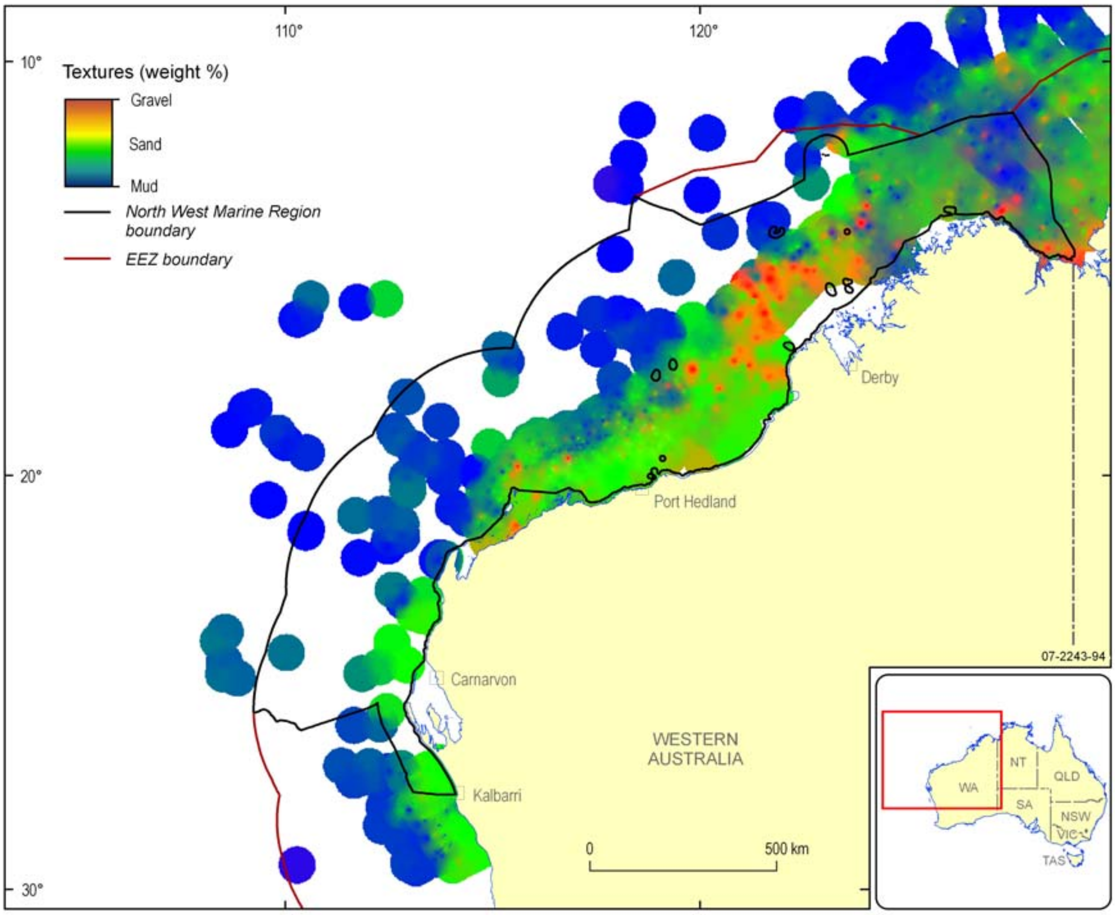
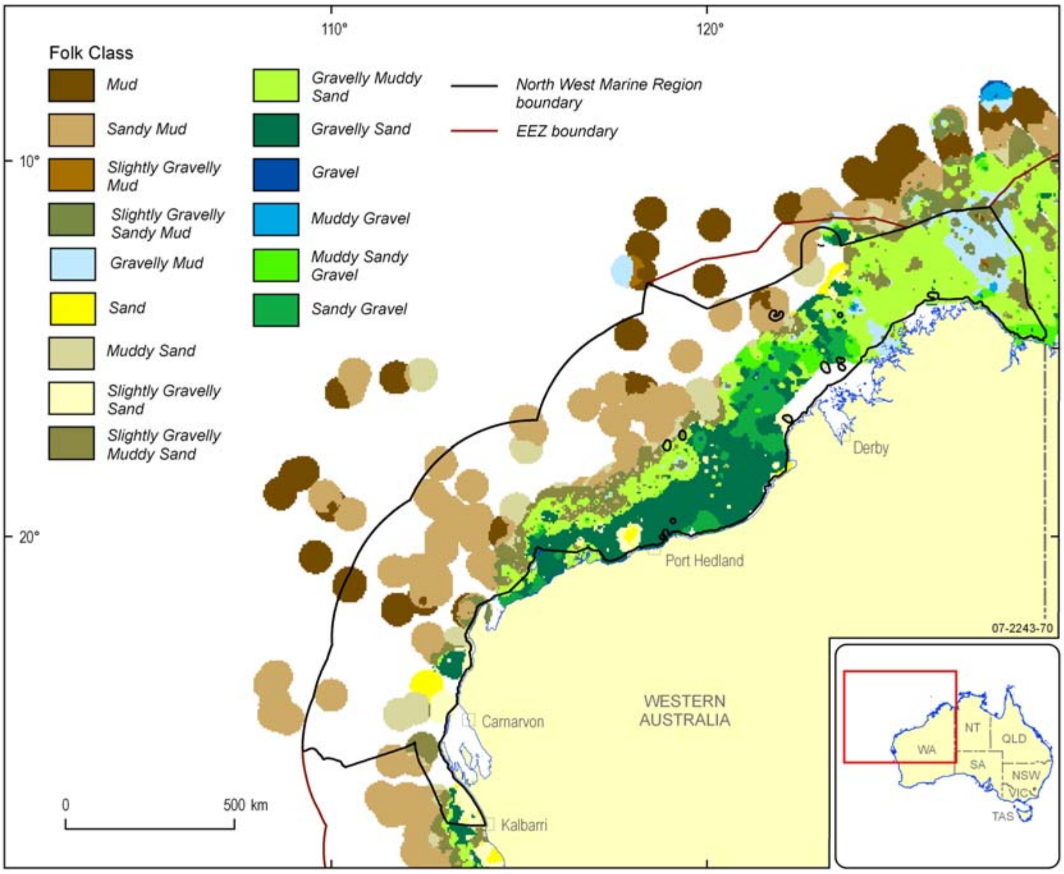


Figure 4.14. Interpolated data for gravel, sand and mud% displayed as an RGB image.

a)



b)

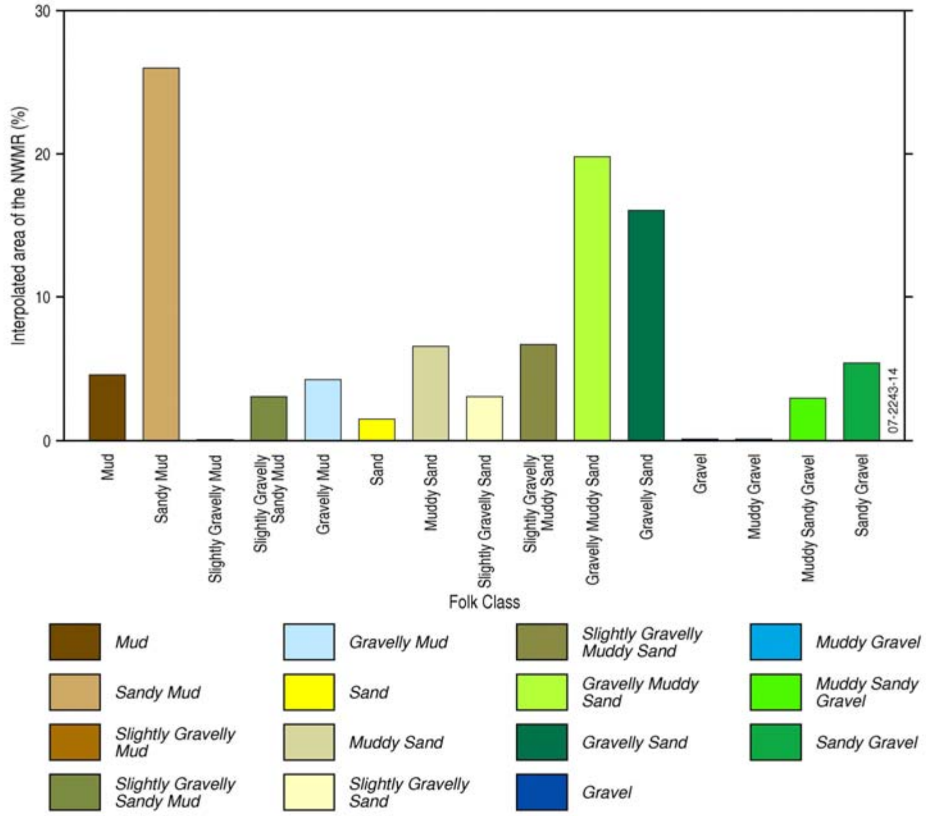


Figure 4.15. a) Interpolated grainsize data displayed as Folk Classes and b) area covered by each class expressed as % of the interpolated area of the NWMR.

4.1.4.2. Sedimentology of Geomorphic Provinces and Significant Features of the NWMR

Quantitative sedimentology is reported for features judged significant at a planning region scale that attain adequate sample coverage. These features cover a large percentage of the NWMR, represent a relatively large percentage of the total area of this feature in the EEZ, or are judged to be unique to the NWMR based on physical properties such as size or water depth range. Where occurrences of a feature form distinct groups based on morphology or water depth, each group has been described separately. Where a feature is judged as significant but does not attain adequate data coverage, features are noted as significant at a planning region or bioregion scale and properties and distribution of sediment within these features are where possible, assessed from previous literature and summarised in Chapter 6.

Features that cover smaller areas of the NWMR but are abundant locally may be judged significant at a bioregion scale. Where samples achieve coverage of only local occurrences of features, for example canyons (Mermaid Canyon, NWP) and deepwater terraces (Rowley Terrace, NWT), the sedimentology of these features is assessed in the context of the bioregion in which they occur.

Shelf Province

The shelf in the NWMR is represented by 449 grainsize and 358 carbonate assays. Over most of the area of the shelf, seabed sediment is characterised by sand (>60%), with less gravel and/or mud (Figs 4.16b & 4.17a). Sand forms >60% of sediment at 293 sites sampled, and >90% at 109 sites. Mud forms >60% of sediment at 28 sites sampled, and >90% at seven sites. Gravel forms >60% at 25 sites sampled, and >90% at seven sites. Sediment containing significant proportions of mud (>20%) are generally restricted to the outer shelf. Sediment containing >40% gravel is also concentrated on the outer shelf, but samples containing up to 80% gravel occur locally on the mid and inner shelf. At the few sites where samples provide coverage of areas on the inner shelf in close proximity to the shoreline, assays indicate that textural composition of sediment in these regions varies greatly, with mud and gravel contents exceeding 90% locally. Variation in sediment composition in these areas occurs at scales smaller than can be detected by existing sample spacing.

In the north of the planning region, on the northern Rowley and Sahul Shelves, sediment containing large proportions of mud and gravel is present across the entire width of the shelf, particularly in the area of the Londonderry Rise and Bonaparte Depression. Approximately 40% of samples from this area contain sediment that is composed of >60% sand.

Carbonate content of sediment exceeds 75% in 242 samples from the shelf and exceeds 90% in 149 samples from the shelf (Fig. 4.17a). Where samples contain gravel, carbonate content of this fraction exceeds 50% at all sites, and exceeds 80% at all except five sites (two of these occur near the coast on the Rowley Shelf). Carbonate content of the sand fraction ranges from 13 to 100% and exceeds 50% in 202 (93%) samples. The exception to this occurs in the Joseph Bonaparte Gulf, where carbonate sand forms <50% in 17 (38%) of the 45 samples in the region. Carbonate content of the mud fraction ranges between 31 and 90% and exceeds 50% in 34 (74%) samples.

Samples containing <50% carbonate are restricted to the following main areas: The Joseph Bonaparte Gulf, Bonaparte Depression and inner shelf adjacent to Port Hedland. Carbonate content varies most significantly in the shallow water areas of the Bonaparte Gulf, where it ranges from <20 to 100%. Carbonate content across the entire Bonaparte Gulf exceeds 50% in <10% of samples however it is frequently <20%. Carbonate content of sediment in this region increases across the shelf outward toward the EEZ boundary.

Slope Province

The slope in the NWMR is represented by 508 grainsize and 456 carbonate assays; these are located mainly near the shelf break. Mud is the dominant fraction across most of the Slope, though spatial clustering of assays means that overall statistics for the province do not reflect this (Fig. 4.16c & 4.17b). Sediment texture is zoned with water depth, with gravel and sand contents decreasing and mud content increasing with increasing water depth.

Mud content of samples on the upper slope varies from <1 to 97% however, sediment composition in this area is highly variable with 134 samples containing <20% mud, reflecting the sedimentology on the adjacent shelf, and approximately 173 samples containing >50% mud. On the middle and lower slope, mud content exceeds 80% at 63 sites sampled and exceeds 60% at more than 161 sites sampled.

Gravel content forms <1% of the sediment fraction at 269 sites sampled. All samples containing >1% gravel were collected within 100 km of the shelf break. Gravel content at these sites ranges from 1 to 92% with the exception of one sample which attained 100% adjacent to terrace and slope features with similar sediment characteristics. 239 samples contained <20% gravel.

Sand content of slope sediment ranges from 3 to 100% with 291 samples exceeding 50%, but it rarely exceeds 40% in areas more than 100 km from the shelf break. Sand ranges from 10 - 40% at >90% of sites sampled on the middle and lower slope.

Carbonate content of sediment on the slope ranges from 41 - 99% with 455 samples containing >50% bulk carbonate. Sediment on the upper slope generally contains >80% carbonate. Mid to lower slope sediment shows variable bulk carbonate content with no apparent zoning with water depth (Fig. 4.17b).

Carbonate content of mud present on the slope shows zoning with water depth. Where sampled, mud on the upper slope contains >80% at approximately 75% of sites. Carbonate content of mud in this area is rarely <60%. Consistently low carbonate content of mud occurs in the far north west of the NWMR on Ashmore Reef. Carbonate content of mud on the lower slope varies but ranges between 60 and 80% at approximately 80% of sites sampled.

Carbonate content of gravel is measured mainly on the upper slope near the shelf break and at 166 sites exceeds 80%. Carbonate content of sand exceeds 80% at 202 sites sampled. These are distributed across all areas of the slope.

Abyssal plain/deep ocean floor

The abyssal plain/deep ocean floor in the NWMR is represented by eight grain size and seven carbonate assays. A total of 42 additional assays from extensions of these features outside the NWMR are also used in the analysis. Sediment from the abyssal plain/deep ocean floor is dominated by mud, comprising >80% mud at approximately 90% of sites sampled (Fig. 4.16a & 4.17c). Samples generally contained no gravel and <10% sand, although one sample attained 18% sand. Bulk carbonate varies from <1 to 79%, with sediment on the Argo Abyssal Plain generally comprising <20% carbonate, while points on the Cuvier Abyssal Plain contain carbonate ranging from 40 to 79% (Fig. 4.17c).

Assays with low mud content and significant sand (ratios <1:1) all occur outside the NWMR. These samples also frequently contain higher carbonate contents than observed within the NWMR. These environments may also occur in the area of the abyssal plain/deep ocean floor within the NWMR but are not detected there due to sparse samples.

Banks/shoals

38 grain size and 39 carbonate assays were obtained from banks/shoals. Sand is the dominant fraction with contents ranging from 1 to 97% (Figs. 4.18a & 4.19a); a total of 19 of the 39 samples contain >50% sand. 10 samples recovered adjacent to basin and terrace features contain lower sand contents of between 1 and 39%. The remaining material is mud, making up between <1 and 92% of sediment volume. 11 samples contain >50% mud, and mud content is >95% in two samples which occur adjacent to sill features. These samples also contain low bulk carbonate contents (<22%) (Fig. 4.19a). Sediment in basins contain <20% gravel in 21 of the 38 samples. However, at one site adjacent to a deeps/holes/valleys feature, one sample comprises 100% gravel. Bulk carbonate content generally varies between 21 and 98% with 29 samples containing >50%. Carbonate sand content ranges between 38 and 100% and attains 100% in 15 samples. Carbonate gravel content varies from 90 to 95% in six samples.

Deep/hole/valleys

A total of 131 samples were obtained from deeps/holes/valleys. Sand is the dominant fraction ranging between 3 and 100% with 91 samples contain >50% sand (Figs. 4.18b & 4.19b). Mud is the next most abundant fraction, ranging in content from <1 to 98% with 20 samples containing >50%. Gravel attains 63% and attains 85% in three samples with a total of six samples exceeds 50%. Bulk carbonate content varies between 42 and 99% with 99 samples exceeding 70% content (Fig. 4.19b). Carbonate sand content varies from 67 to 100% with four samples attaining 100%. Carbonate mud content ranges between 33 and 91% with 31 samples exceeding 70%. Carbonate gravel content varies between 90 and 100% but attains 55% in one sample, with 29 samples attaining 100%.

Basins

A total of 26 samples were obtained from basins. At a planning region scale, basins show a common sedimentology that distinguishes them from other geomorphic features (Fig. 4.18c & 4.19c). Mud is the dominant fraction; Contents range between 9 and 97%, and a total of 15 of the 26 samples containing >50% mud. Four samples recovered from near the shelf break contain lower mud contents, ranging between 9 and 33%. The remainder of sediment volume comprises sand ranging in content from 3 to 66%, although two samples occur in an area of low mud content and contain 76% sand. Sediment in basins generally contain no gravel. However, low gravel content (1-23%) is observed occasionally at a range of locations in basins sampled. Bulk carbonate content generally varies between 29 and 72%, where data is available (Fig. 4.19c). Carbonate sand content ranges from 27 to 100% and attains 100% in 12 samples. No carbonate mud or gravel contents were measured for existing samples in basins due to small sample volumes available for analysis (<10g).

Reefs

A total of three samples were obtained from reefs. Sand is the dominant fraction with contents ranging from 52 to 94% (Fig. 4.18d) Gravel is the next most abundant fraction with contents attaining 30%. Mud attains 35% where sand content is low. Laser grainsize distribution for this sample is included in Appendix F. Bulk carbonate content of sediment ranges from 64 to 97%.

Ridges Located in Shallow Water

A total of 18 grain size and 17 carbonate assays were obtained from ridges located in shallow water (<200 m). Mud is the dominant fraction with contents ranging from between <1 and 76% and exceeding 50% in 11 samples (Figs. 4.18e & 4.19d). Sand is the next most abundant fraction with contents ranging from 23 to 99% and dominating the sediment (>80%) in five samples. Gravel content is generally <10%, although in two samples located adjacent to terrace and slope features gravel ranges from 20 to 36%. Bulk carbonate content of sediment exceeds 80% in all but one sample (Fig. 4.19d). Carbonate mud content ranges between 88 and 89% in six samples. Carbonate sand content ranges between 93 and 98%, and carbonate gravel varies from 60 and 100% and attains 100% in six samples.

Plateaus on the Shelf or near the Shelf Break

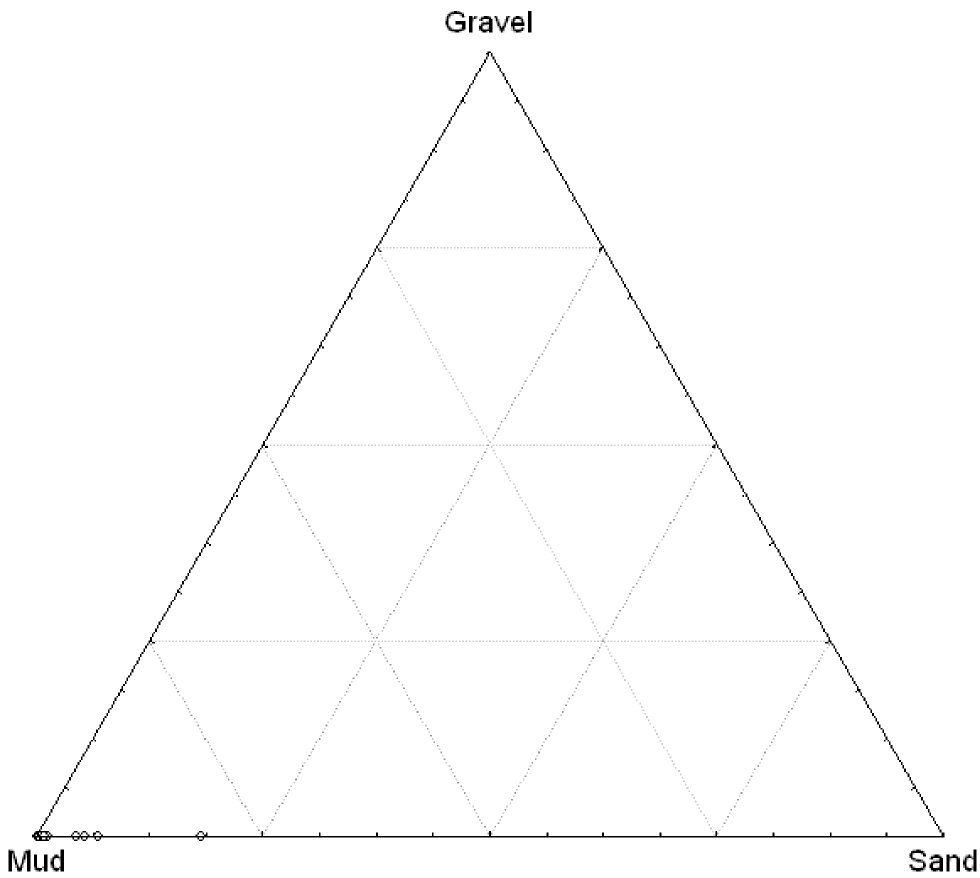
A total of 24 grain size and 22 carbonate assays were obtained from plateaus located on the shelf or near the shelf break. Sand is the dominant size fraction in sediments; Contents range from 25 to 100% with a total of 17 samples containing >50% sand (Figs. 4.18f & 4.19e). However, one sample from the slope adjacent to a pinnacle contains <5% sand. Mud is the next most abundant fraction with contents generally ranging from <1 to 44% with a total of eight samples containing >20% mud. Gravel content ranges from 3 to 100% with five samples containing >50%. Bulk carbonate content generally varies from 17 to 99% with a total of 19 samples containing >50% carbonate (Fig. 4.19e). Carbonate sand ranges between 14 and 99% with 10 samples exceeding 50%. Carbonate mud ranges between 31 and 90%. Carbonate gravel attains 95% for five samples.

Offshore Plateaus and Terraces

A total of 37 grain size and 36 carbonate assays were collected from offshore plateaus and terraces. Mud is the most abundant fraction; Contents range from 10 to 93% with 28 samples containing >50% mud. Sand is the next most dominant size fraction with contents generally range from 6 to 89% (Figs. 4.18g & 4.19f) and exceed 50% in seven samples. Two samples did not contain sand, mud or gravel volumes adequate for analysis. Gravel content is <2% in all samples. Bulk carbonate content ranges from 50 to 88% with 28 samples containing >70% carbonate (Fig. 4.19f). Carbonate sand content ranges between 85 and 99% with 21 samples exceeding 90%. Carbonate mud content varies from 51 to 87% with 20 samples exceeding 70%. Carbonate gravel content attains 100% in seven samples.

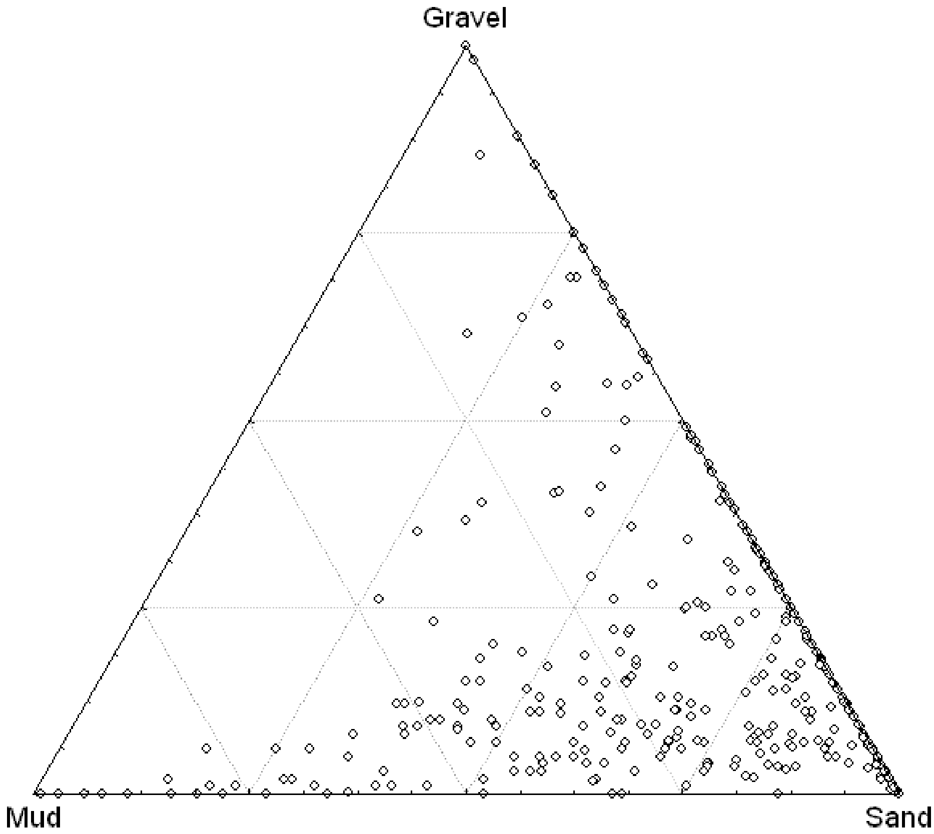
Terraces Located on the Shelf or Near the Shelf Break

A total of 193 samples were collected from terraces located on the shelf or near the shelf break. Sand is the dominant fraction in sediment with contents generally ranging from 8 to 100% (Figs. 4.18h & 4.19g); a total of 143 of the 193 samples contain >50% sand. Mud is the next most abundant fraction and highly variable, with contents ranging from <1 to 91%. A total of 34 of the 193 samples contain >50% mud. Gravel content ranges from <1 to 88%, and attains 100% in one sample; a total of five samples contain >50% gravel. Bulk carbonate content of sediment generally ranges from 42 to 99% with 167 samples exceeding 50% carbonate content (Fig. 4.19g). Carbonate sand content varies between 58 and 99% with 68 samples exceeding 80% content. Carbonate mud content ranges from 44 to 90% with 29 samples exceeding 60%. Carbonate gravel content varies between 90 and 100% and attains 100% in 24 samples.



a)

b)



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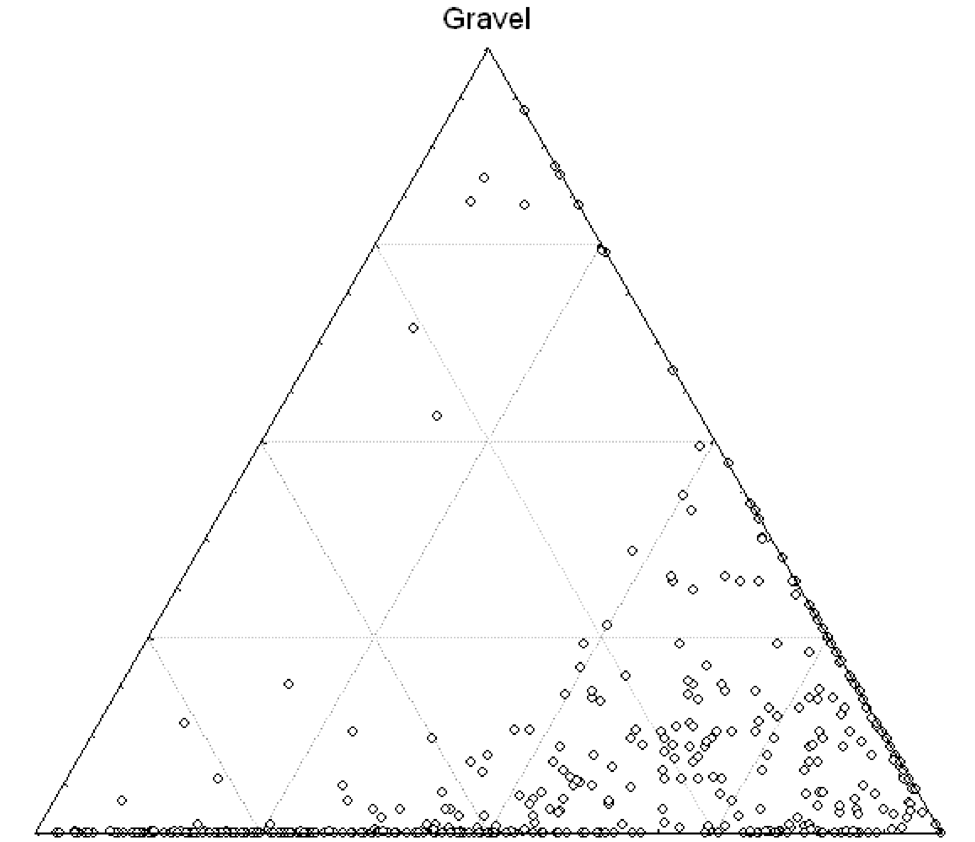
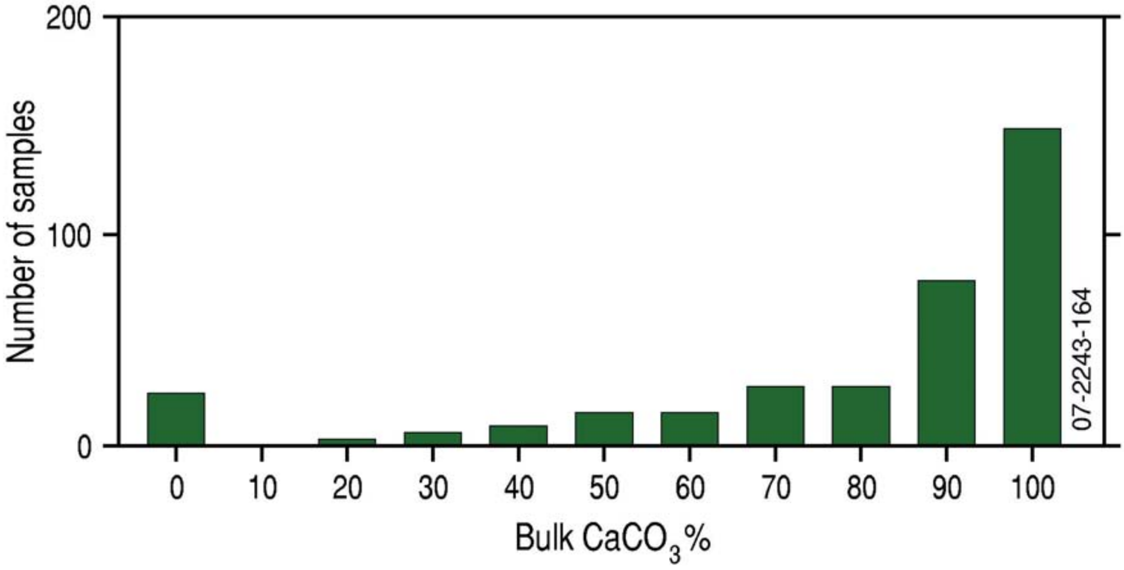


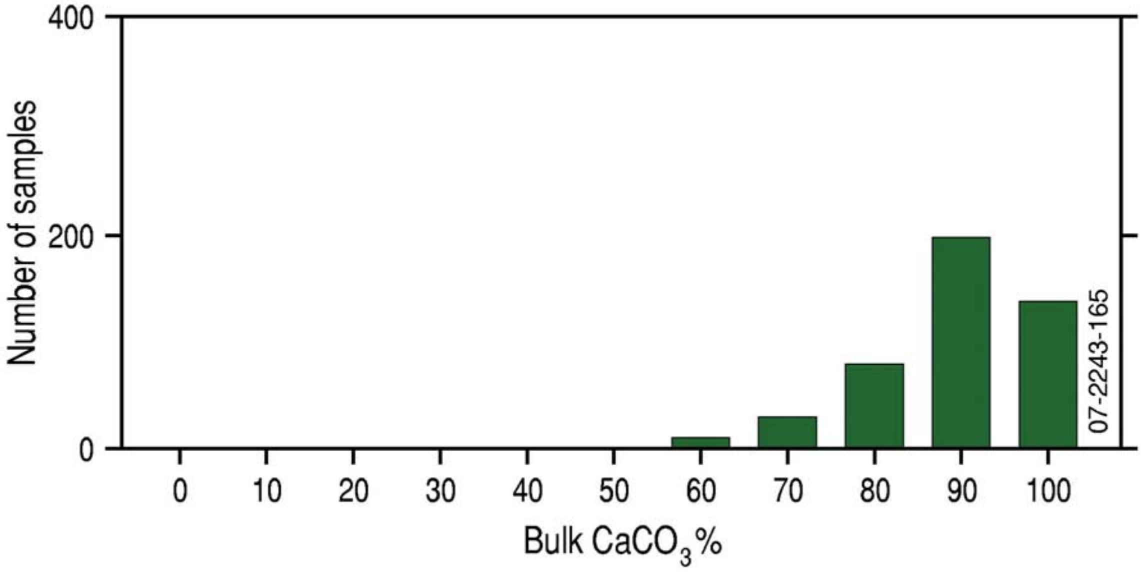
Figure 4.16. Textural composition (mud:sand:gravel ratio) of geomorphic provinces in the NWMR: a) abyssal plain/deep ocean floor province; b) shelf province; and c) slope province sediments within the NWMR.

a)



200
100
0
Number of samples
07-2243-164
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%

b)



400
200
0
Number of samples
07-2243-165
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%

c)

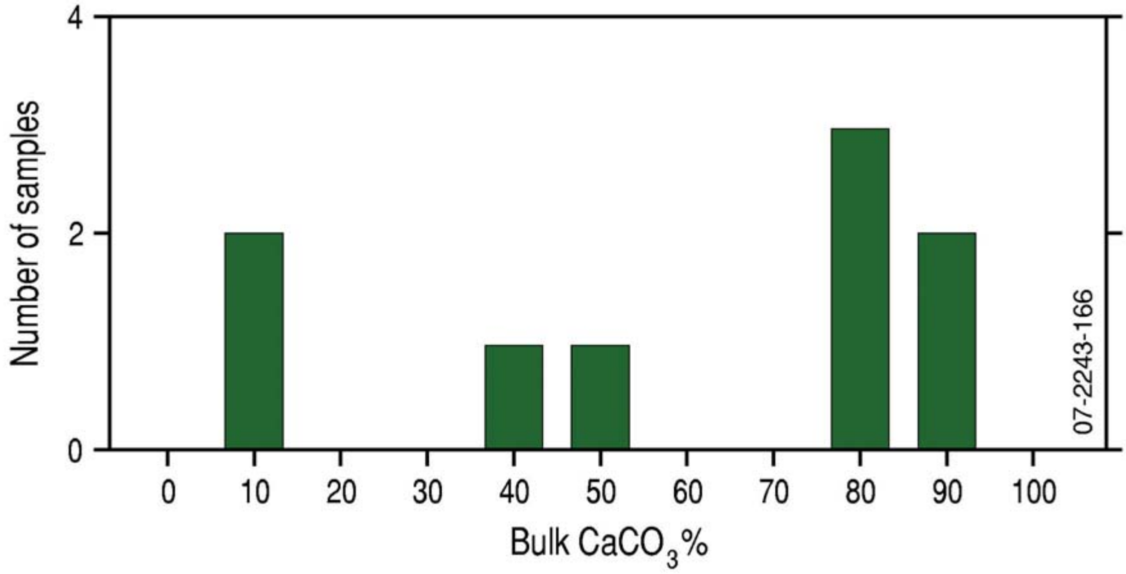
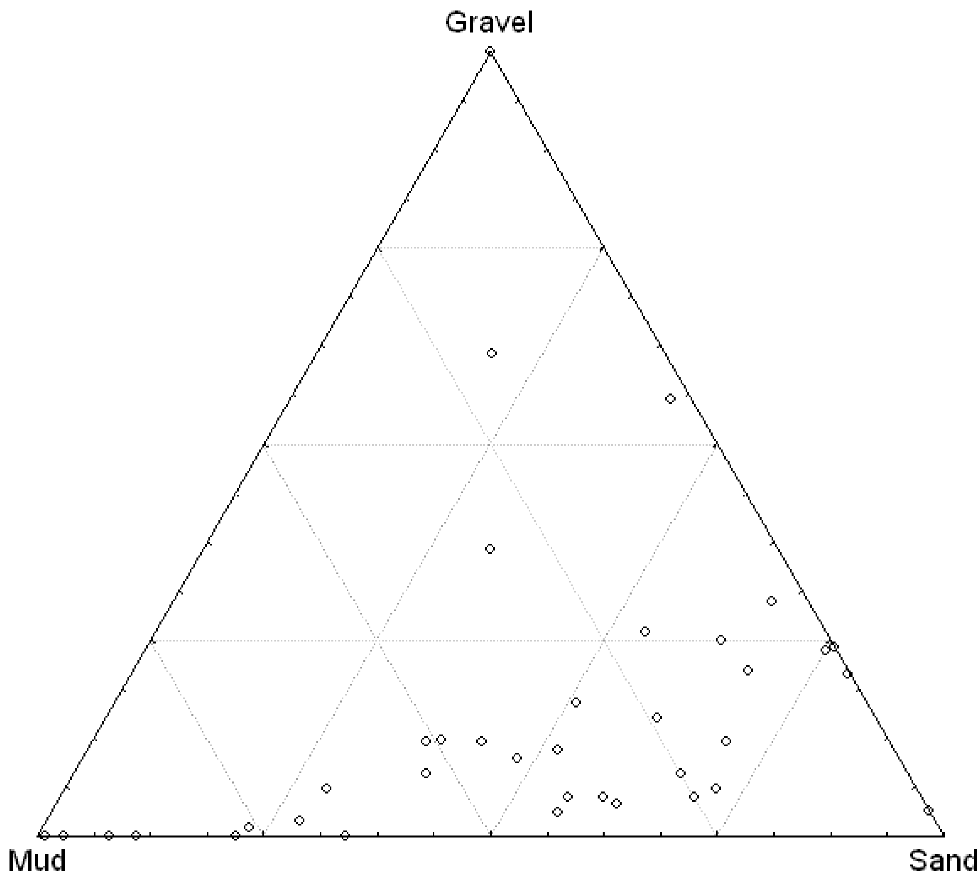
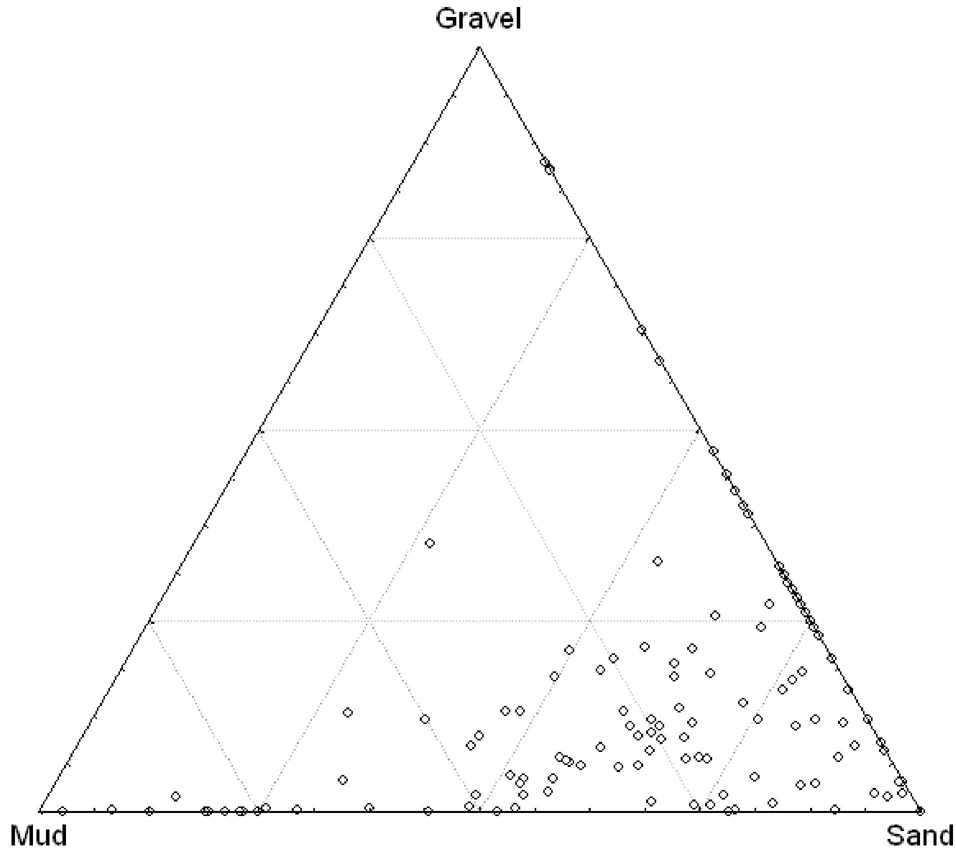


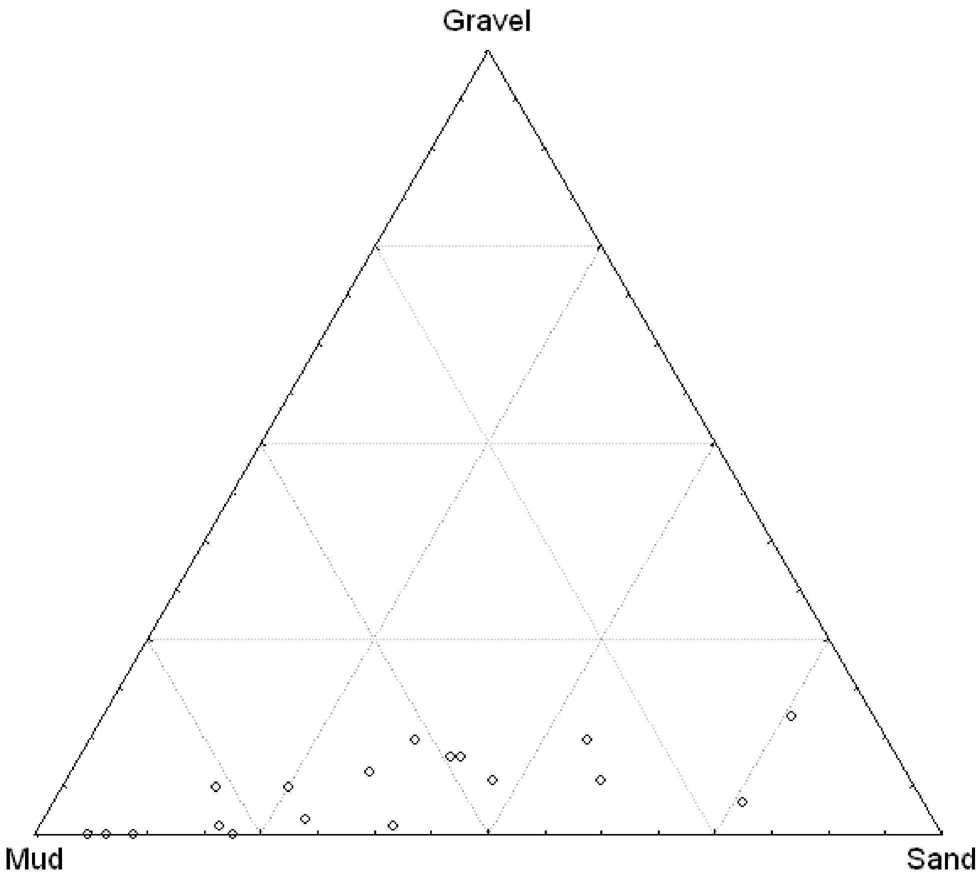
Figure 4.17. Carbonate content of geomorphic provinces within the NWMR: a) shelf province; b) slope province; and c) abyssal plain/deep ocean floor province.

a)



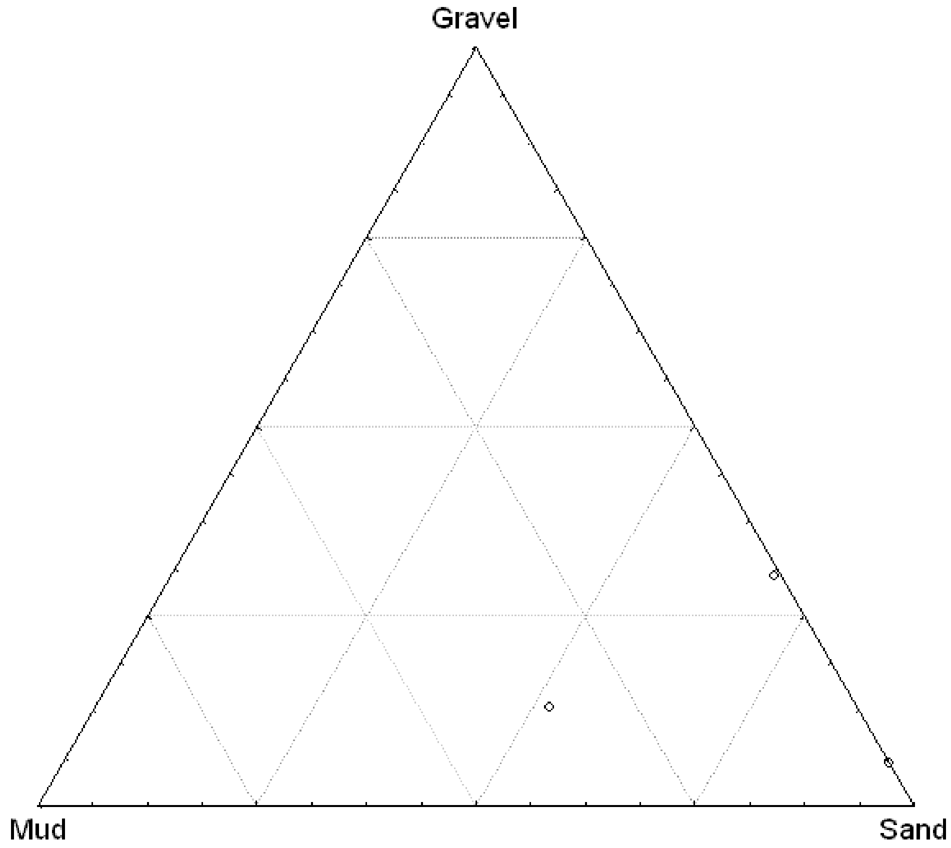
b)

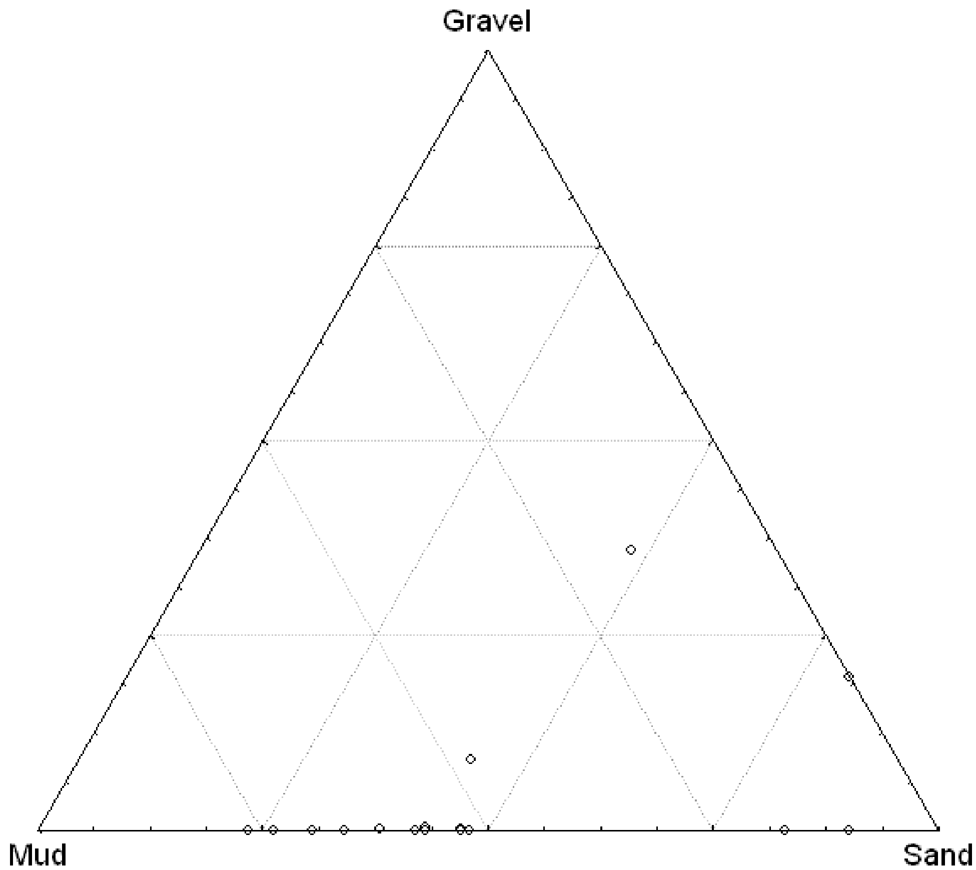




c)

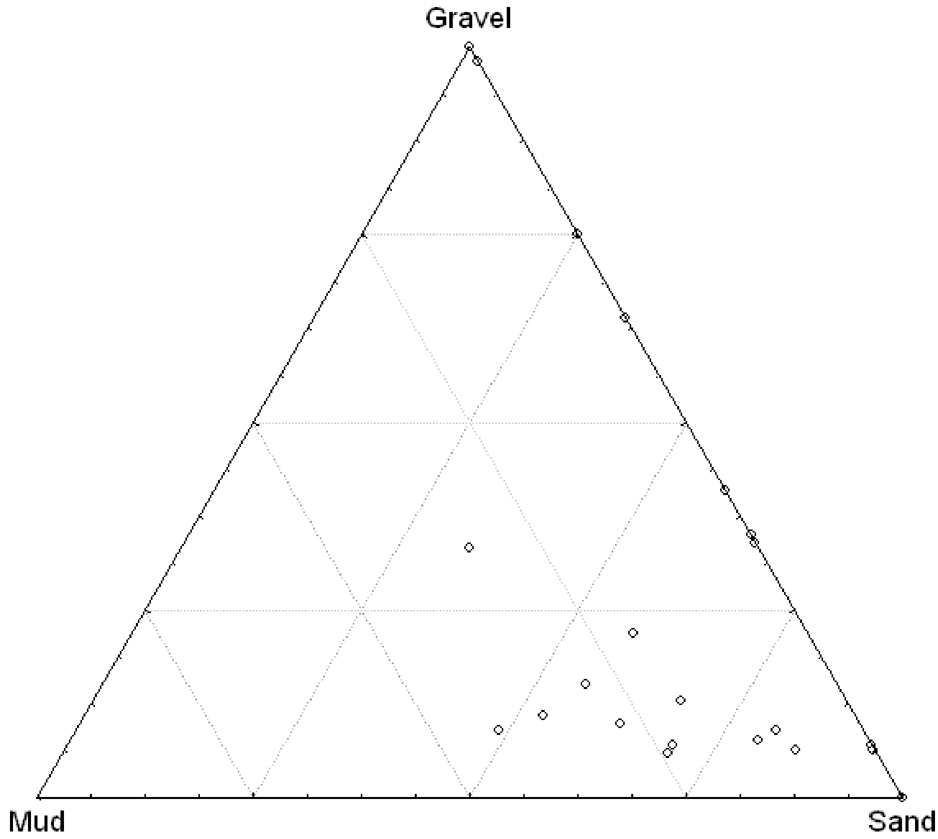
d)



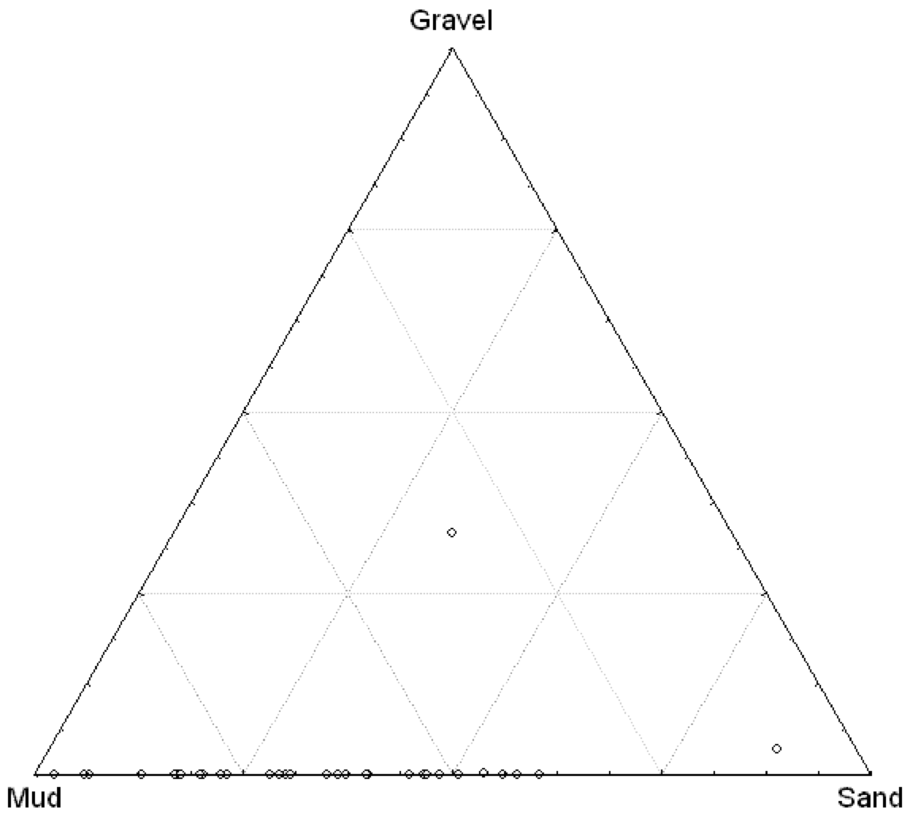


e)

f)



g)



h)

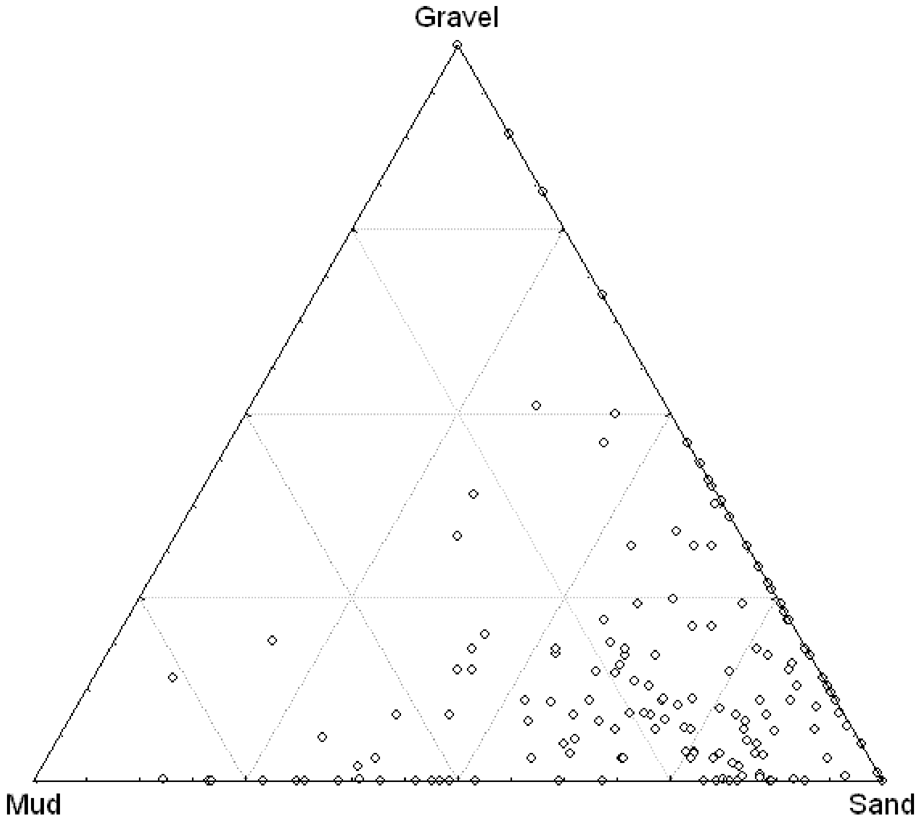
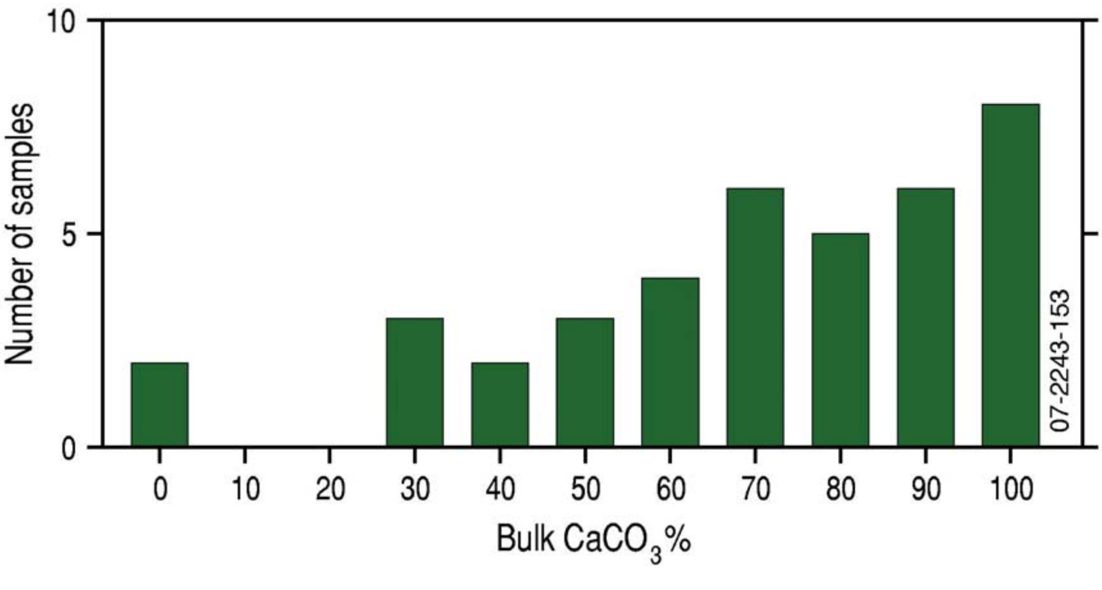
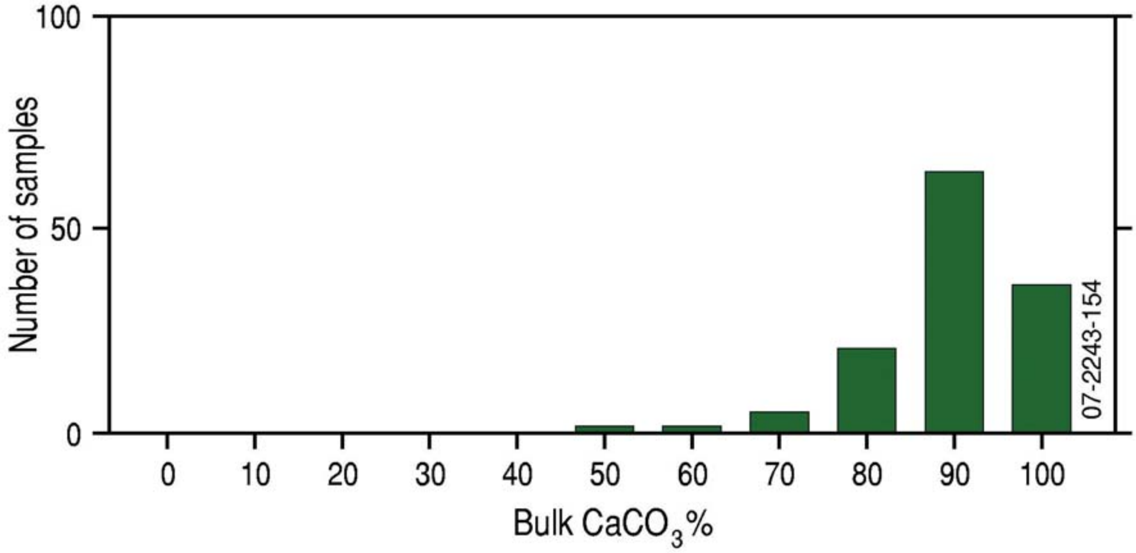


Figure 4.18. Textural composition (mud:sand:gravel ratio) of significant geomorphic features in the NWMR: a) bank/shoal; b) deep/hole/valley; c) basin; d) reef; e) ridges located in shallow water; f) plateaus on the shelf or near the shelf break; g) offshore plateaus and terraces; and h) terraces located on the shelf or near the shelf break.

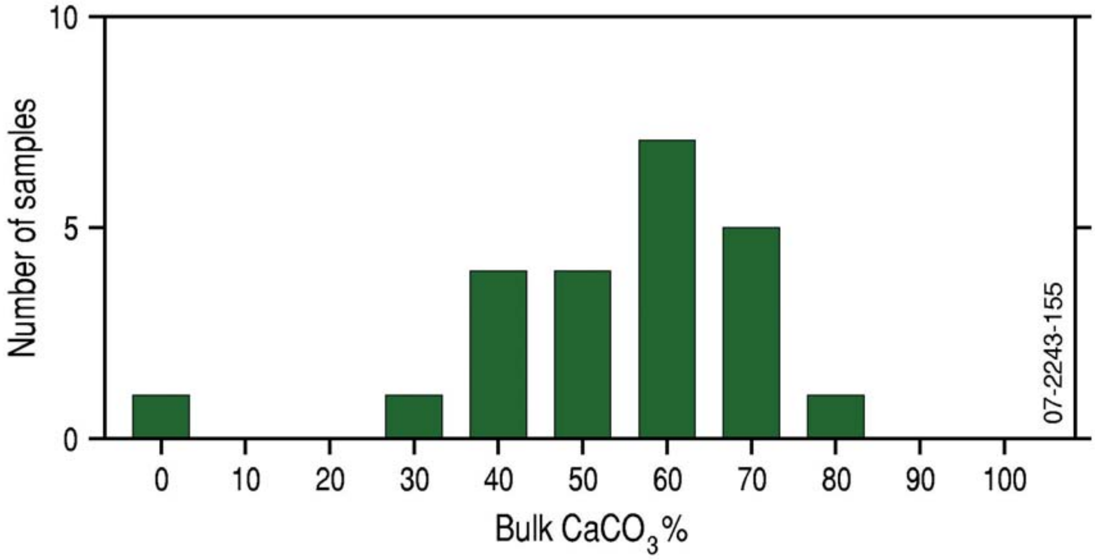
a)



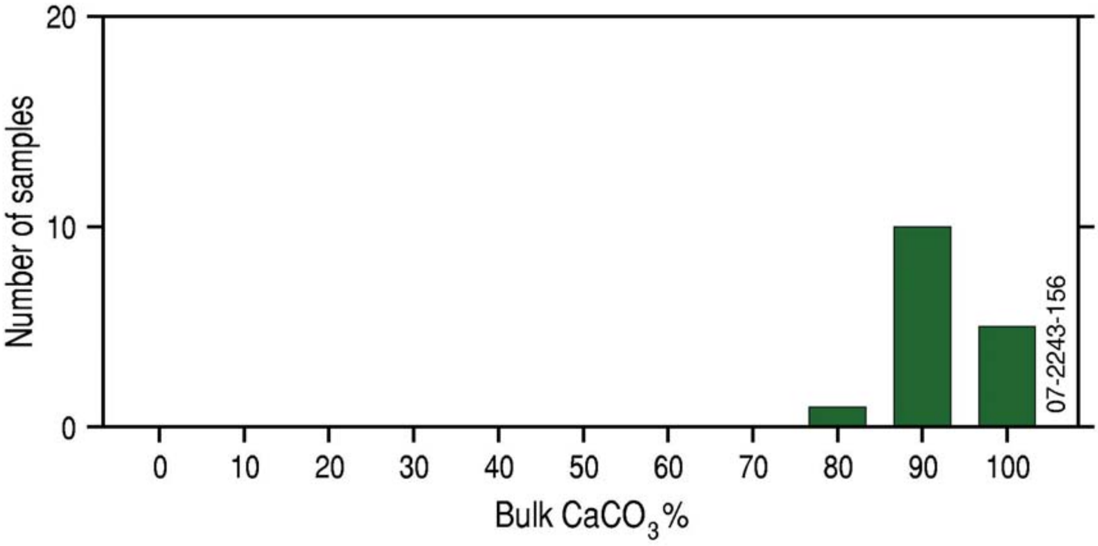
b)


100
50
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-154

c)

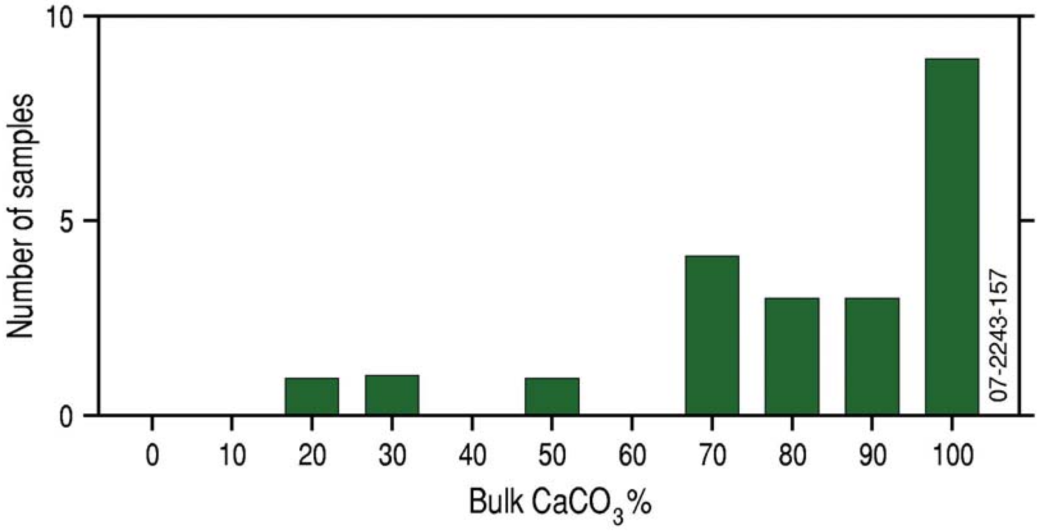

10
5
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-155

d)



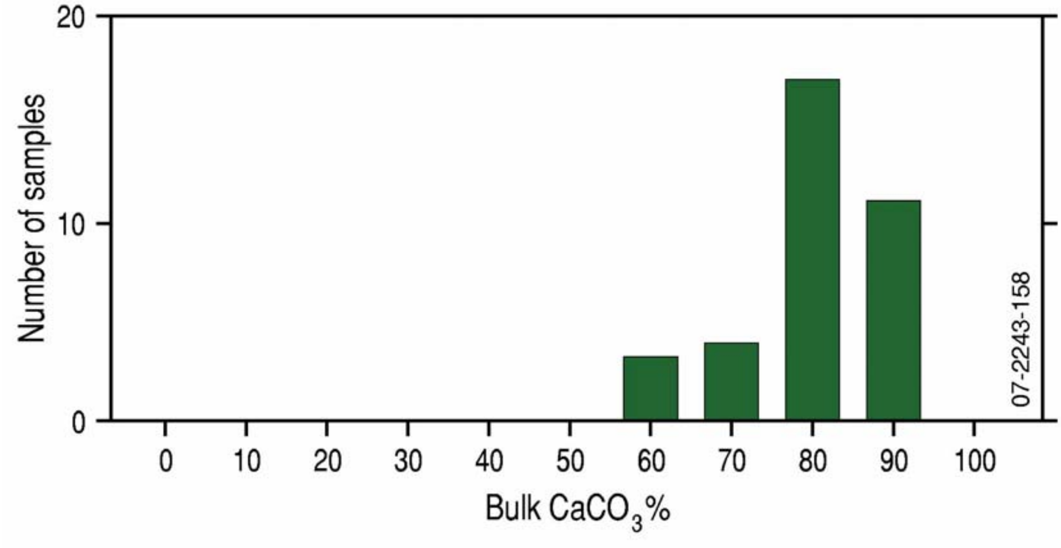
20
10
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk CaCO3%
07-2243-156

e)



10
5
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk CaCO3%
07-2243-157

f)



20
10
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk CaCO3%
07-2243-158

g)

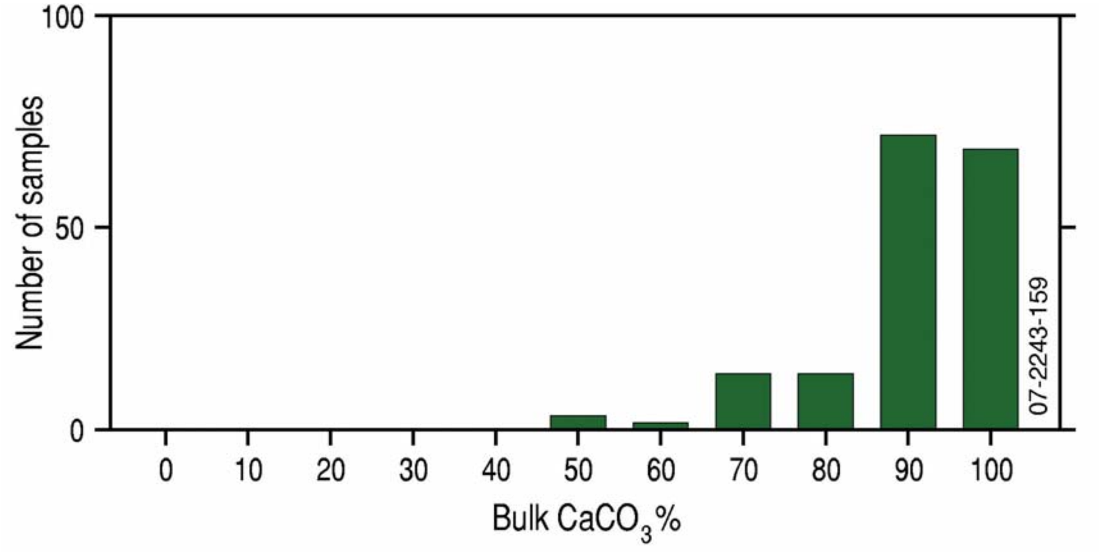


Figure 4.19. Carbonate content of geomorphic features within the NWMR: a) bank/shoal; b) deep/hole/valley; c) basin; d) ridges located in shallow water; e) plateaus on the shelf or near the shelf break; f) offshore plateaus and terraces; and g) terraces located on the shelf or near the shelf break

4.2. QUANTITATIVE DESCRIPTION OF THE NNMR

4.2.1 Geomorphology

Two geomorphic provinces occur in the NNMR (Fig. 4.20; Table 4.3). The shelf makes up the largest area (89%, 143,010 km²), followed by the slope (11%, 17,580 km²). The NNMR does not contain abyssal plain/deep ocean floor or continental rise provinces.

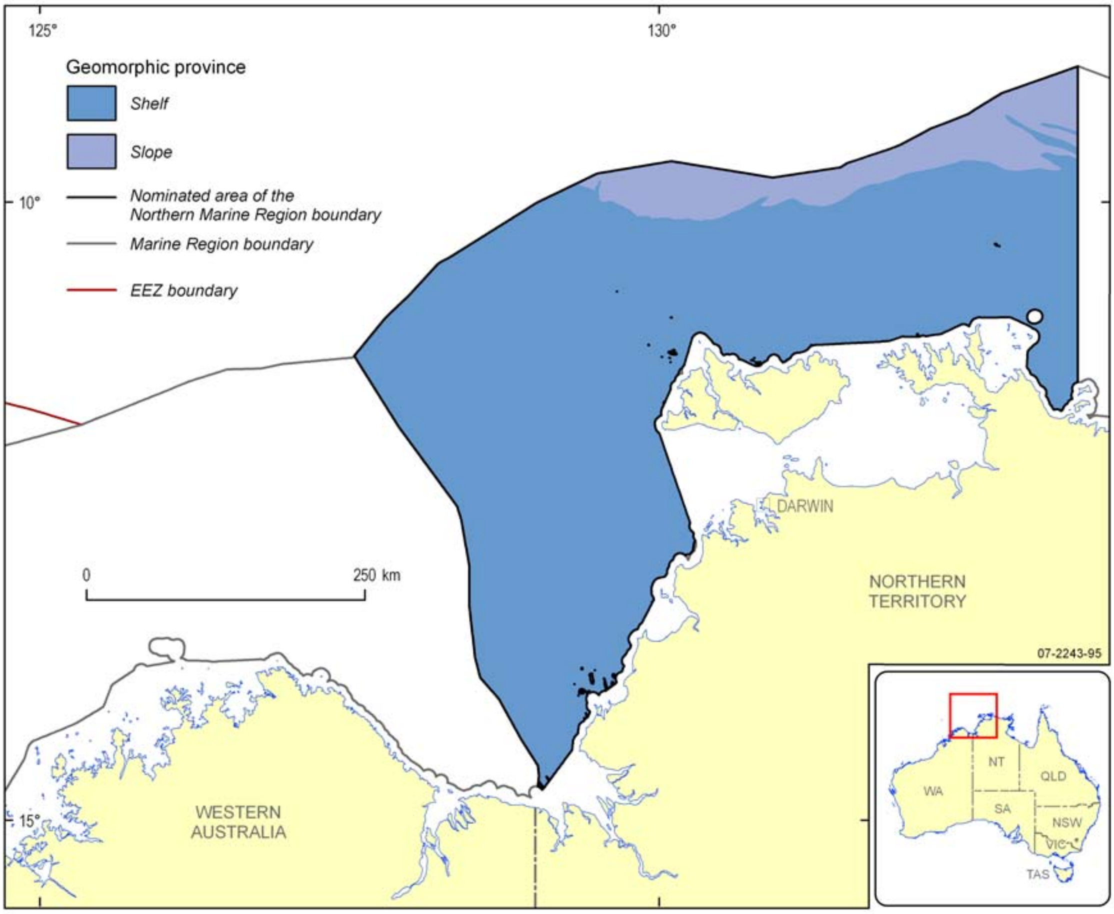
Of the 21 geomorphic features defined on the Australian margin, 12 are represented in the NNMR. Including shelf, slope, banks/shoals, deeps/holes/valleys, basin, reef, canyon, ridge, pinnacle, aprons/fans, terrace, and tidal sand wave/sand bank (Fig. 4.21; Table 4.3). Unassigned shelf covers 56% (90,660 km²) of the NNMR. The remaining area of shelf is comprised of banks/shoals, deeps/holes/valleys, tidal sand wave/sand banks and pinnacles. Unassigned slope covers <4% (5,680 km²) of the NNMR. The remaining area of the slope is comprised of canyons, apron/fans, deeps/holes/valleys, ridges, terraces, reefs and pinnacles.

A large proportion of the total area of aprons/fans and banks/shoals in the EEZ occur in the NNMR. The NNMR contains 33% (2,150 km²) of the total area of aprons/fans found in the EEZ and 17% (8,770 km²) of banks/shoals (Table 4.3).

Table 4.3. Statistics of geomorphic provinces and features of the NNMR.

Feature	Area in NMR	% total NMR Area	% EEZ Area	% Total area of features in EEZ located in NMR	Water Depth Range in NMR (m)	Water Depth Mean in NMR (m)
Geomorphic Province						
Shelf	143,010	89.05	21.76	5.21	15 - 290	70
Slope	17,580	10.95	44.42	0.46	15 - 380	170
Geomorphic Feature						

Shelf	90,660	56.45	13.79	7.31	5 - 195	65
Slope	5,680	3.54	15.23	0.41	20 - 320	200
Bank/Shoals	8,770	5.46	0.56	17.19	5 - 155	45
Deep/Hole/Valley	6,300	3.92	1.83	3.70	5 - 290	85
Basin	18,810	11.71	7.36	2.63	40 - 250	110
Reef	440	0.28	0.52	0.91	5 - 205	65
Canyon	1,820	1.13	1.18	1.70	120 - 245	140
Ridge	190	0.12	1.24	0.16	120 - 215	160
Pinnacle	360	0.23	0.06	6.59	10 - 350	115
Apron/Fan	2,160	1.35	0.13	32.67	120 - 250	195
Terrace	25,130	15.65	6.43	4.36	10 - 380	95
Tidal Sandwave/Sand Bank	270	0.17	0.27	1.15	10 - 55	25
TOTAL	*160,590*					



a)

b)

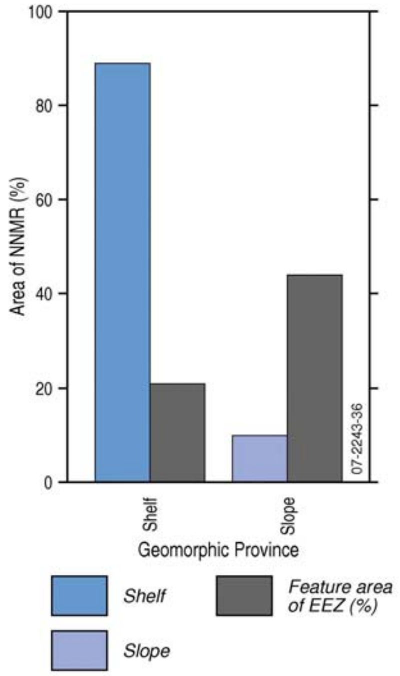
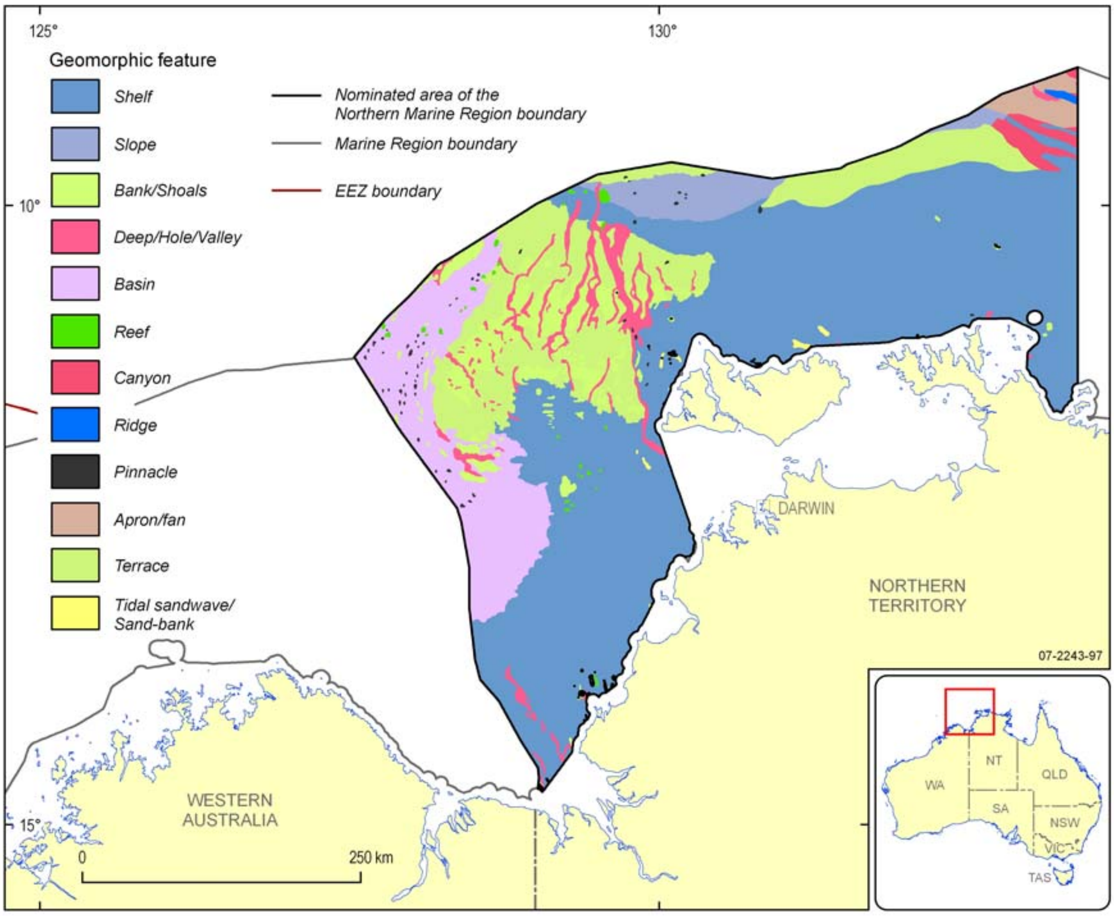


Figure 4.20. a) Geomorphic Provinces of the nominated area of the Northern Marine Region (NNMR); and b) Percentage area of each geomorphic province within the NNMR and EEZ.


125°
130°
10°
15°
Geomorphic feature
Shelf
Slope
Bank/Shoals
Deep/Hole/Valley
Basin
Reef
Canyon
Ridge
Pinnacle
Apron/fan
Terrace
Tidal sandwave/
Sand-bank
Nominated area of the
Northern Marine Region boundary
Marine Region boundary
EEZ boundary
DARWIN
NORTHERN
TERRITORY
WESTERN
AUSTRALIA
0
250 km
07-2243-97
WA
NT
QLD
SA
NSW
VIC
TAS

a)

b)

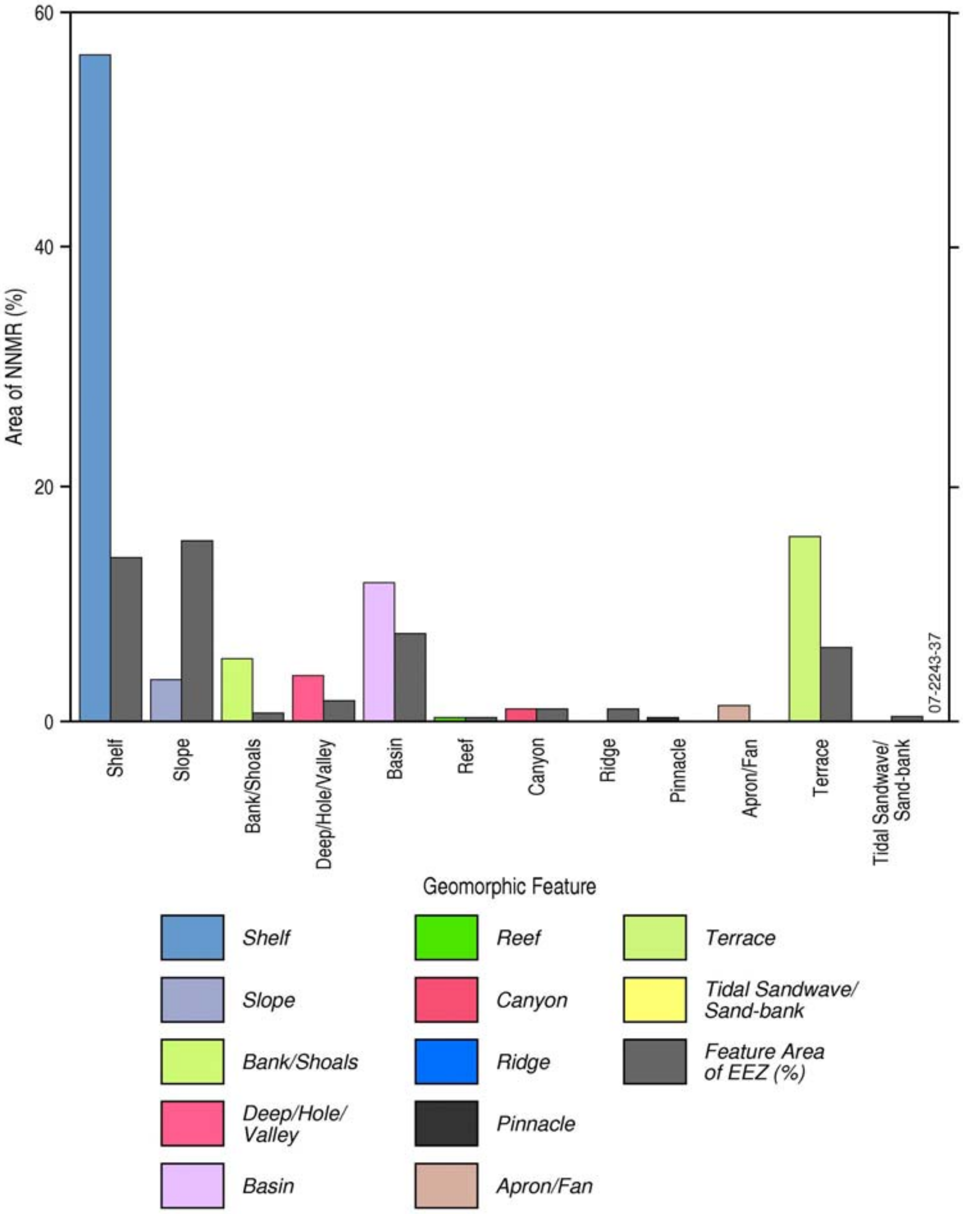


Figure 4.21. a) Geomorphic Features of the nominated area of the Northern Marine Region (NNMR); and b) Percentage area of each geomorphic feature within the NNMR and EEZ.

4.2.2. Bathymetry

The NNMR is relatively shallow with water depths ranging from 5 – 380 m (Table 4.4; Fig. 4.24). Approximately 75% of the total area occurs in water depths shallower than 100 m and approximately 25% in water depths between 100 and 350 m. Shallow water depths in the NNMR reflect the broad continental shelf of Australia's northern margin.

Ridges, canyons, pinnacles and aprons/fans in the NNMR occur at a limited water depth range compared to those found in the remaining Australian margin. In the NNMR these features are restricted to water depths shallower than 350 m (Table 4.3). Elsewhere in the EEZ, a large proportion of these features occur in water depths greater than 500 m (Potter et al., 2006).

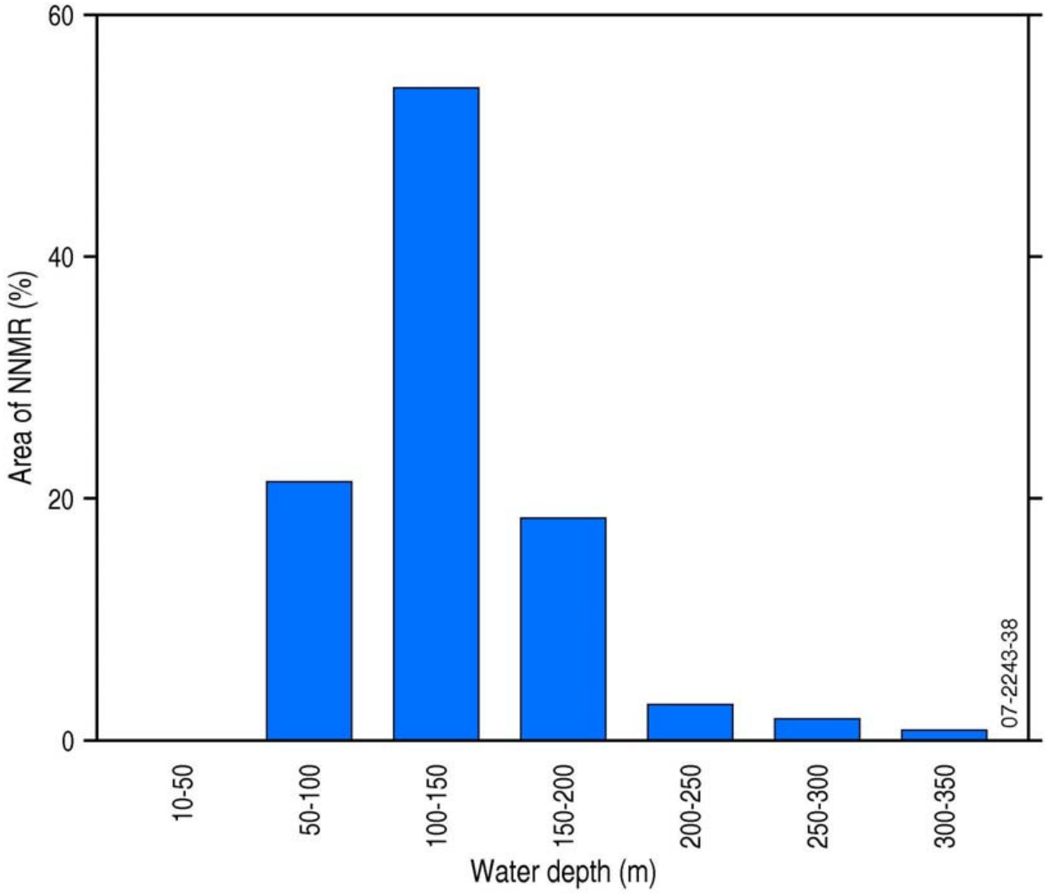


Figure 4.22. Distribution of water depth classes by percentage area within the nominated area of the Northern Marine Region (NNMR).

4.2.3. Sediment Data Coverage in the NNMR

4.2.3.1. Quantitative Textural and Compositional Data

Sample distribution is relatively consistent across the NNMR (Fig. 4.23.). More than 80% of the total area of the NNMR contains between 10 and 50 samples per 1,000 km^2. Less than 3% of the total area has a density of <1 sample per 1,000 km^2. Lowest sample densities occur locally on the inner shelf and in the northwest corner of the NNMR (Fig. 4.24.). Samples are abundant and relatively evenly distributed across the remainder of the region (Fig. 4.24.).

A total of 272 samples (86% of samples in the NNMR) are from on the shelf, resulting in an average sample density of 1.9 samples per 1,000 km^2 (Fig. 4.24.; Table 4.4). A total of 46 (14%) samples are from the slope, giving a sample density of >2.6 samples per 1,000 km^2. This sample coverage is considered adequate to assess the sedimentology for nine of the 12 geomorphic features present in the NNMR, including banks/shoals, deeps/holes/valleys, basins, canyons, ridges, aprons/fans and terraces. No samples were collected from reefs or pinnacles. One sample was collected from tidal sand wave/sand banks. Together, reefs, pinnacles, and tidal sand waves/sand banks, cover approximately 1,080 km^2 (<1%) of the NNMR (Table 4.4).

Of those features containing adequate samples for analysis, highest sample density occurs on ridges (27 samples per 1,000 km²) and aprons/fans (4.6 samples per 1,000 km²). Low numbers of samples and/or clustering of samples on some features mean that assays may not be representative of seabed properties for the entire feature across the NNMR. For example, tidal sand wave/sand banks average 3.7 samples per 1,000 km² but this is based on only one sample (Table 4.4). Low sample numbers may affect results for tidal sand wave/sand banks, canyons and ridges. Spatial clustering may significantly affect results for aprons/fans, deeps/holes/valleys, and ridges.

The distribution of all samples from the NNMR spans water depths between 10 and 315 m (Fig. 4.26). A total of 289 (90%) samples occur in water depths <150 m, and 15 samples (5%) occur in water depths >200. Sample coverage adequately represents the distribution of water depths in the NNMR with 233 (73%) samples present in areas of water depths <100 m that cover approximately 75% of the total area.

Table 4.4. Description of average density of samples in each geomorphic province and feature.

PROVINCE/ # Feature	**No. sample points**	**% NWMR Area**	**Average sample density (samples per 1,000 km²)**
Geomorphic Province			
Shelf	272	89.05	1.90
Slope	46	10.95	2.62
Geomorphic Province			
Shelf (unassigned)	185	56.45	2.04
Slope (undivided)	15	3.54	2.64
Bank/shoals	13	5.46	1.48
Deep/hole/valley	12	3.92	1.90
Basin	32	11.71	0.00
Reef	0	0.28	2.20
Canyon	4	1.13	26.86
Ridge	5	0.12	0.00
Pinnacle	0	0.23	4.63
Apron/fan	10	1.35	1.63
Terrace	41	15.65	3.65
Tidal sand wave/sand bank	1	0.17	1.70

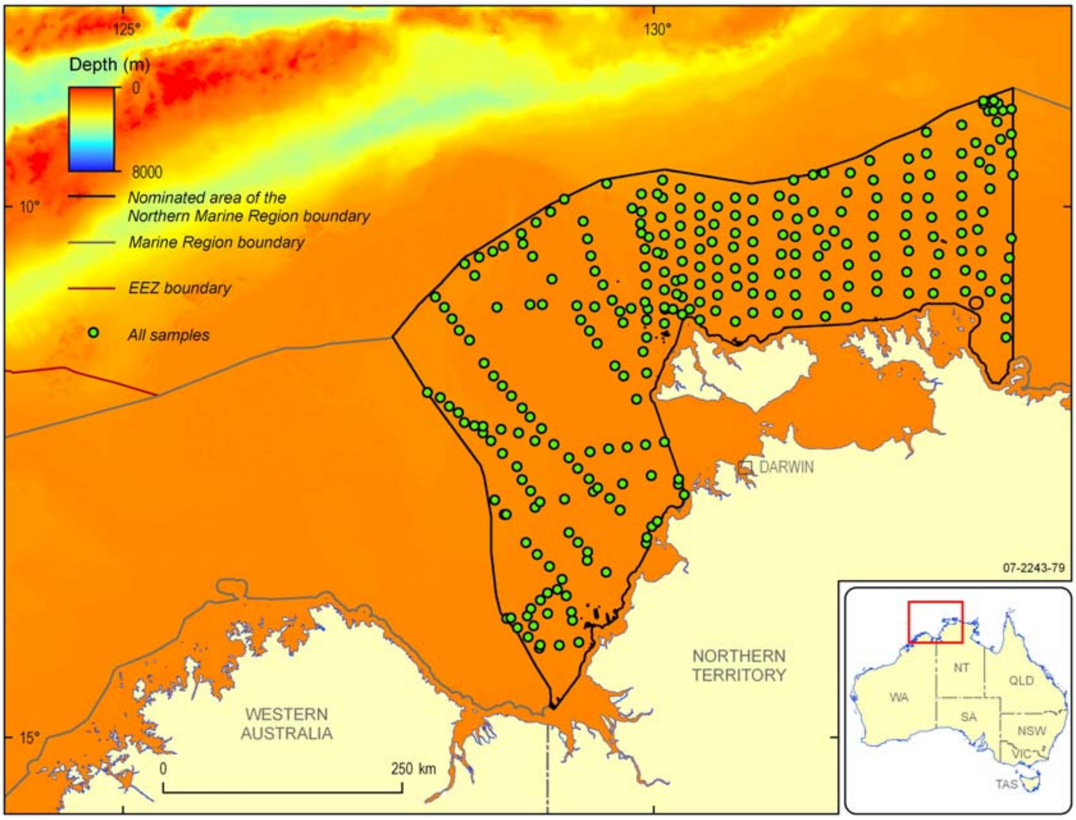
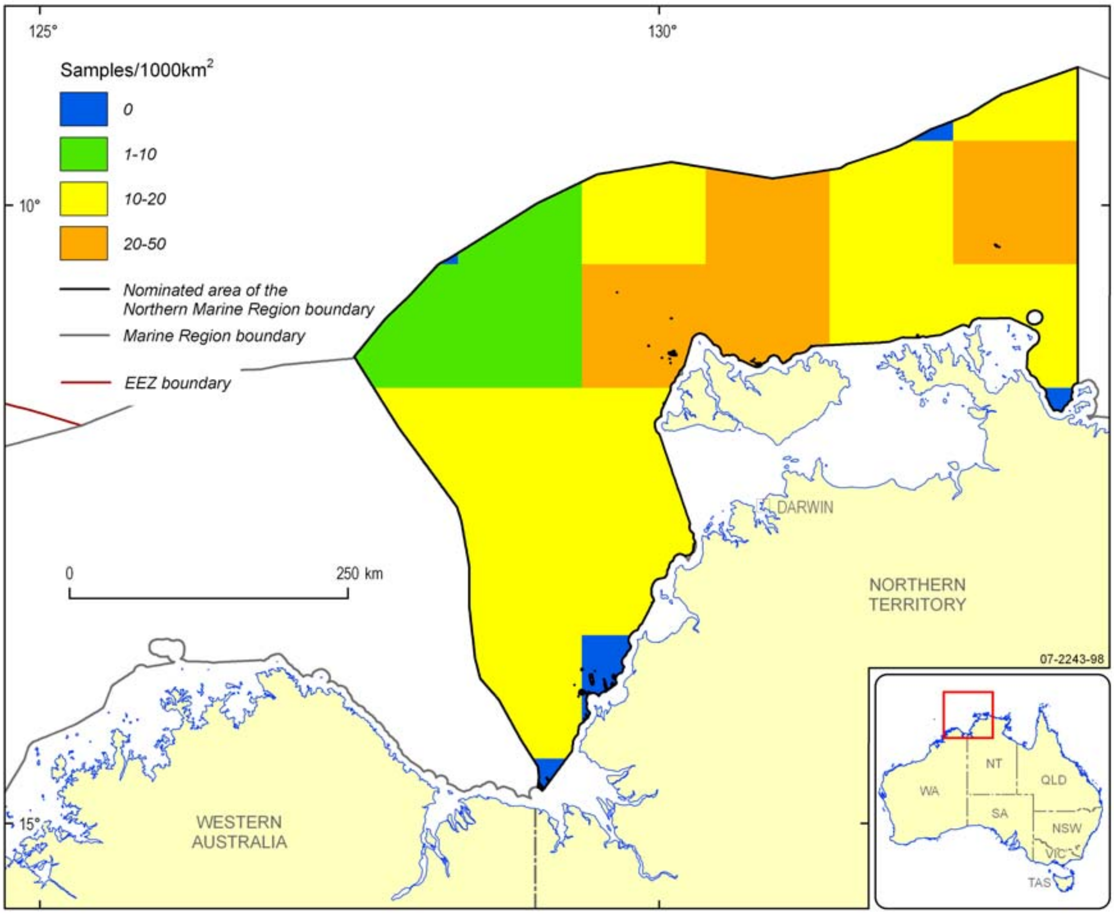


Figure 4.23. Location of all quantitative textural and compositional sample points for the NNMR in relation to bathymetry.



a)

b)

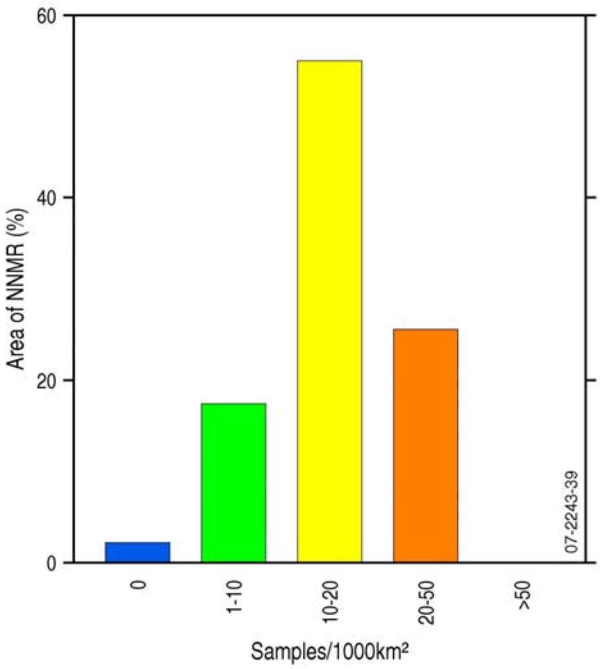


Figure 4.24. a) Sample density distribution across the NNMR and b) frequency distribution of sample density.

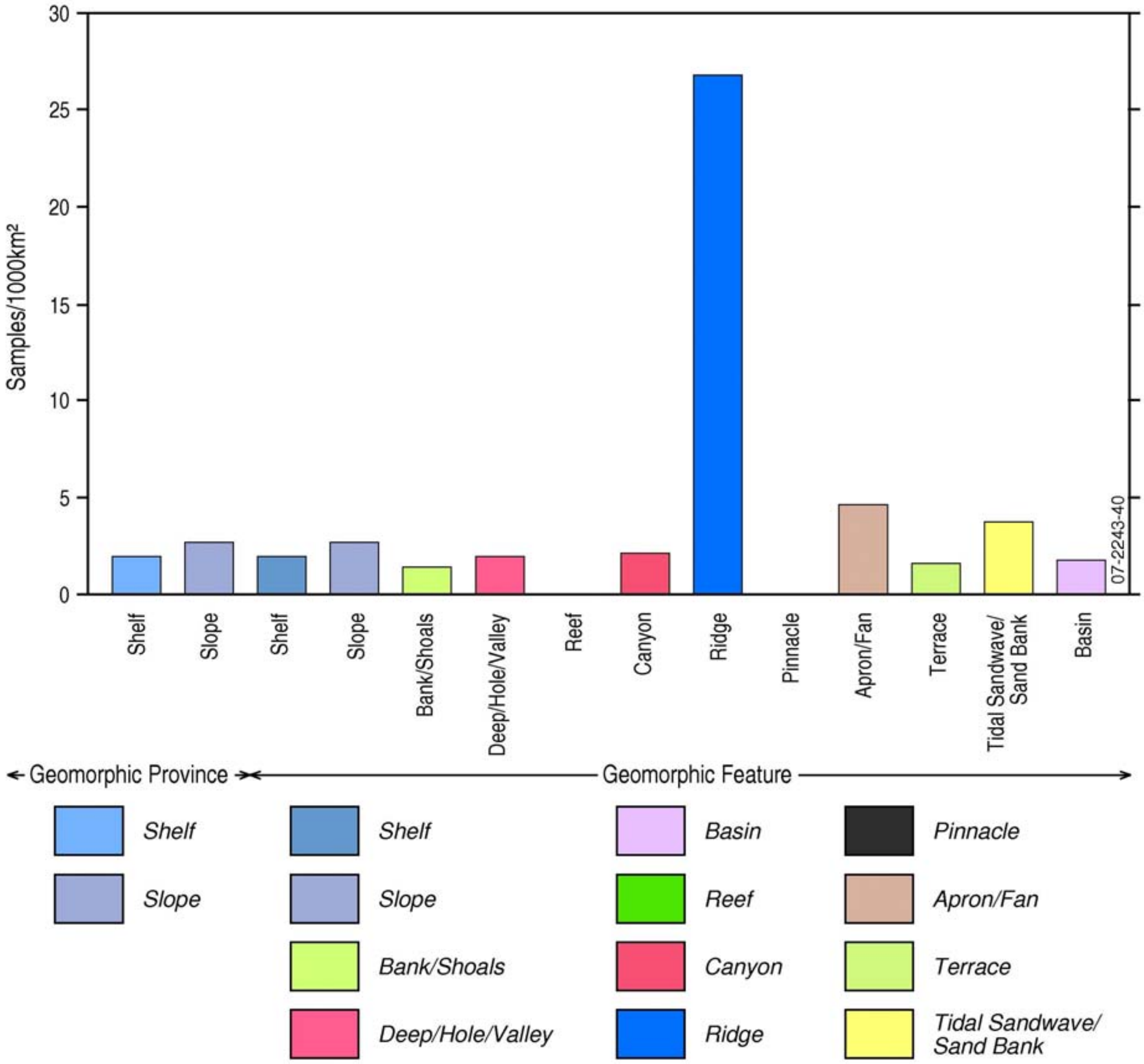


Figure 4.25. Sample densities of geomorphic provinces and features for the NNMR (y axis shows average density measured as samples per 1,000 km²).

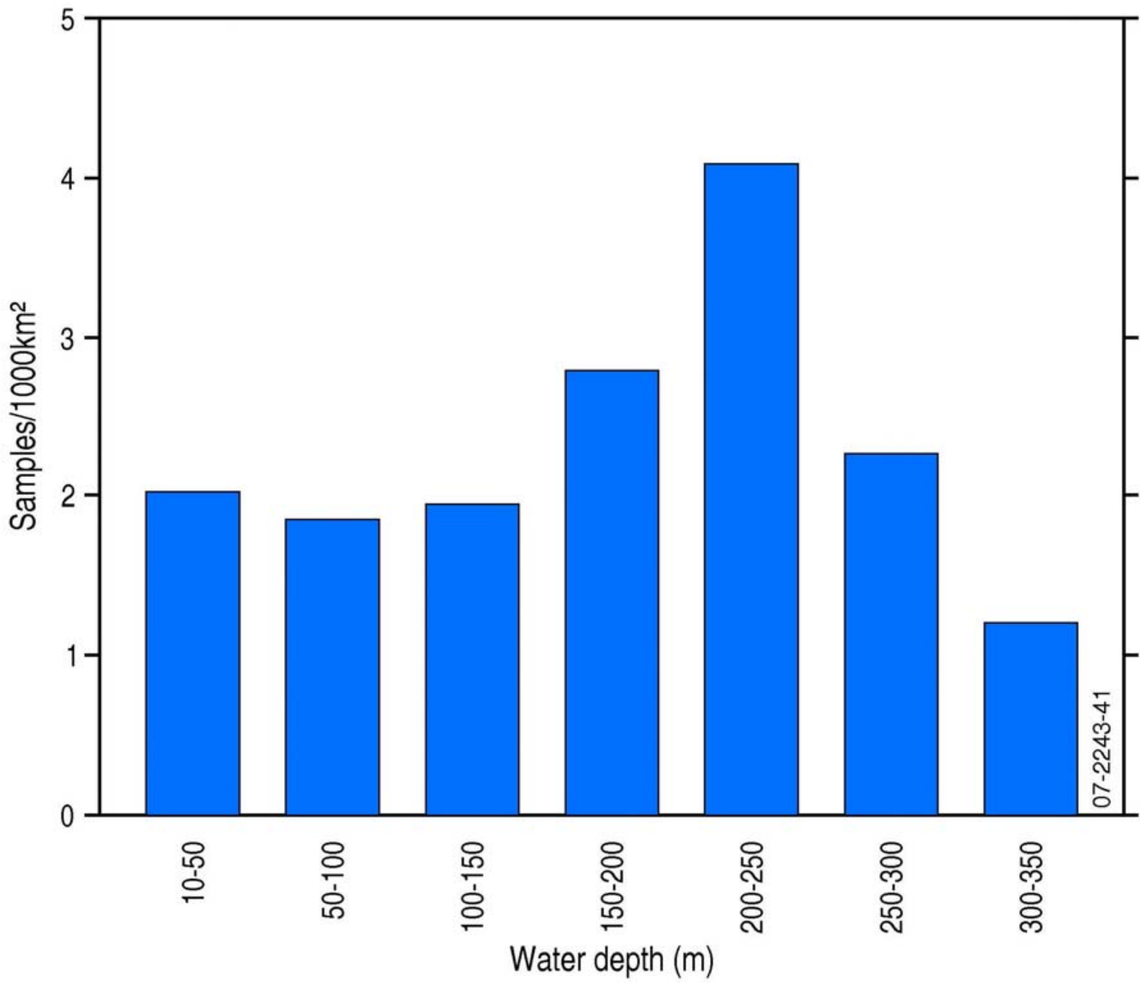


Figure 4.26. Sample densities for water depths for the NNMR (y axis shows average density measured as samples per 1,000 km²).

4.2.4. Quantitative regional sediment distribution in the NNMR

4.2.4.1. Overview of Distribution and Properties

Sample assays indicate that the seabed of the NNMR is characterised by a range of sediment types (Fig. 4.29, 4.30, 4.31 & 4.33). Sand is the dominant size fraction and ranges from 0 – 94%. A total of 250 samples (80%) contain >20% sand, and 89 samples (30%) contain >70% sand. Sand content is highest in samples located within the Joseph Bonaparte Gulf and on the outer shelf adjacent to the Van Diemen Rise (Fig 4.32). Mud content ranges from 0 – 100% and is highest to the northwest of Melville and Bathurst Islands where it comprises 80 - 100% of the total sediment volume (Fig 4.29). Elsewhere, mud content is significantly lower with 189 (60%) samples containing <50% mud and 45 (14%) containing <10% mud.

Gravel was detected in 208 (65%) samples but is the dominant size fraction in only two samples (<1%). Gravel forms a minor component (<10%) of sediment in 230 samples (72%). Gravel occurs most frequently on the inner shelf and within banks/shoals and aprons/fans of the Van Diemen Rise (Fig. 4.31a). The abundance and distribution of sediment containing gravel is likely to be underrepresented in the data due to sparse sample coverage of areas of the NNMR closest to the coast (Fig. 4.23).

Sediments are predominantly calcareous with 179 samples (68%) containing >40% carbonate and 109 (41%) containing >70% carbonate (Fig. 4.28). Carbonate content generally decreases with increasing water depth and is highest within the Joseph Bonaparte Gulf and area surrounding the Van Diemen Rise (Fig. 4.32a). In these areas the carbonate content of sediments generally exceeds 60%. To the northeast of Melville and Bathurst Islands carbonate content is lower, generally between 20 and 40%.

Sand and gravel fractions within the NNMR are dominated by carbonate grains. The carbonate content of the sand fraction is known for 113 samples and ranges from 28 – 100%. A total of 105 (93%) samples contain sand that is >50% carbonate, and 75 (67%) contain sand that is >90% carbonate. The distribution of carbonate sand varies spatially with lower carbonate concentrations frequently observed in sand occurring nearest to the coast. Carbonate forms 100% of the gravel fraction in three (100%) samples occurring on the slope. These samples represent deeper water (>160 m) occurrences of gravel within the NNMR. The carbonate content of the mud fraction is generally lower, ranging from 22 – 31%.

Sediment assays were interpolated using the methods described in Chapter 2 to give an estimate of regional distribution of sediment properties in the NNMR. Interpolated grainsize data achieves coverage of approximately 160,300 km^2 (99%) of the total NNMR. Interpolated bulk carbonate data and Folk classification cover a similar area.

Sediment texture and composition in the NNMR vary spatially from east to west and with increasing water depth. Areas with the highest mud (>80%) and lowest sand (<20%) content are located to the north east of Melville and Bathurst Islands, while areas with the highest sand (>80%) and lowest mud (<20%) content are located to the west of these islands. Mud and bulk carbonate content increase with increasing water depth and are highest on the outer shelf and slope (Fig. 4.29a & 4.29b). Bulk carbonate content is highest in sand dominated areas, predominantly to the west of Melville and Bathurst Islands where carbonate content ranges from 60 to 100%. Carbonate content is lowest (<40%) to the north of the Van Diemen Gulf. Gravel forms a minor component (<20%) of sediment in the NNMR. However, deposits of gravel (20 to 60% of sediment volume) occur locally in close proximity to the coast (Fig. 4.31a & 4.31b).

The Folk Classification (Fig 4.33) shows that the shelf to the north of Melville Island is dominated by gravely muddy sand (gmS) with smaller quantities of slightly gravely muddy sand ((g)mS) and gravely sand (gS) to the east of Melville Island. The slope is dominated by slightly gravely muddy sand ((g)mS) north of Melville Island. In the northeast area of the NNMR, sediments are a combination of slightly gravely sandy mud ((g)sM), gravely mud (gM) and muddy sandy gravel (msG). The abundance of muddy sand (mS), slightly gravely sandy mud ((g)sM) and sandy mud (sM) increase with increasing water depth and are most common within the slope province. A notable change in the sedimentology occurs to the north east of Melville and Bathurst Islands where an increase in the deposition of gravelly muddy sand (gmS) is observed.

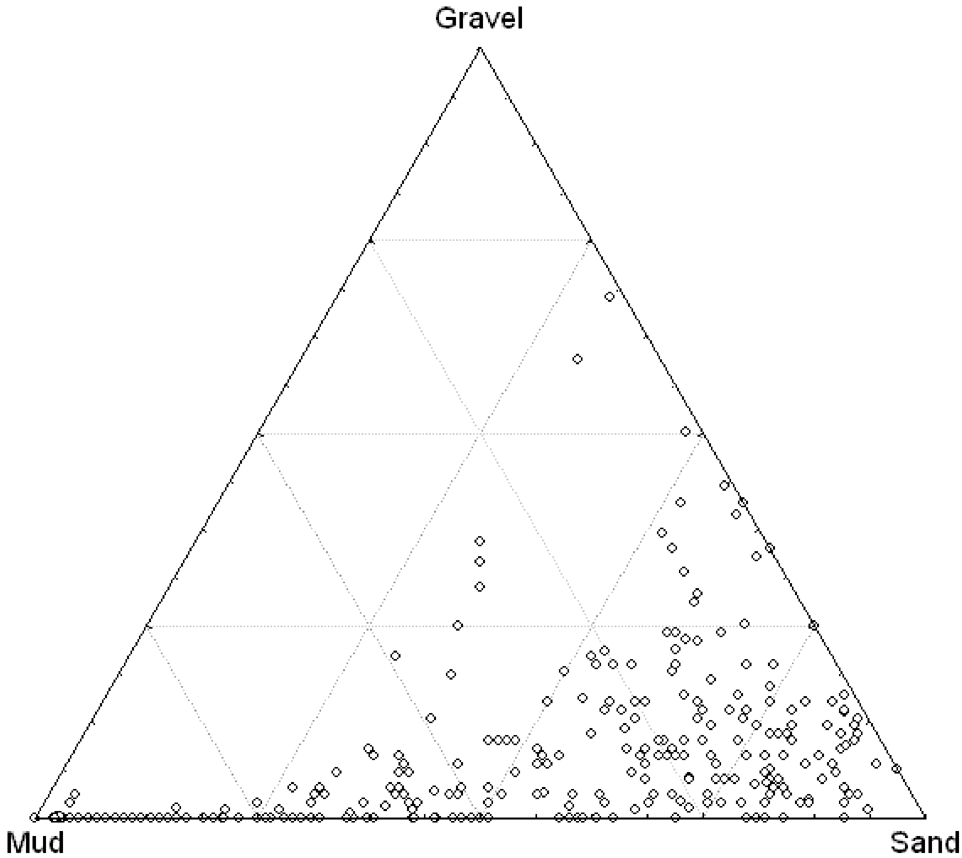
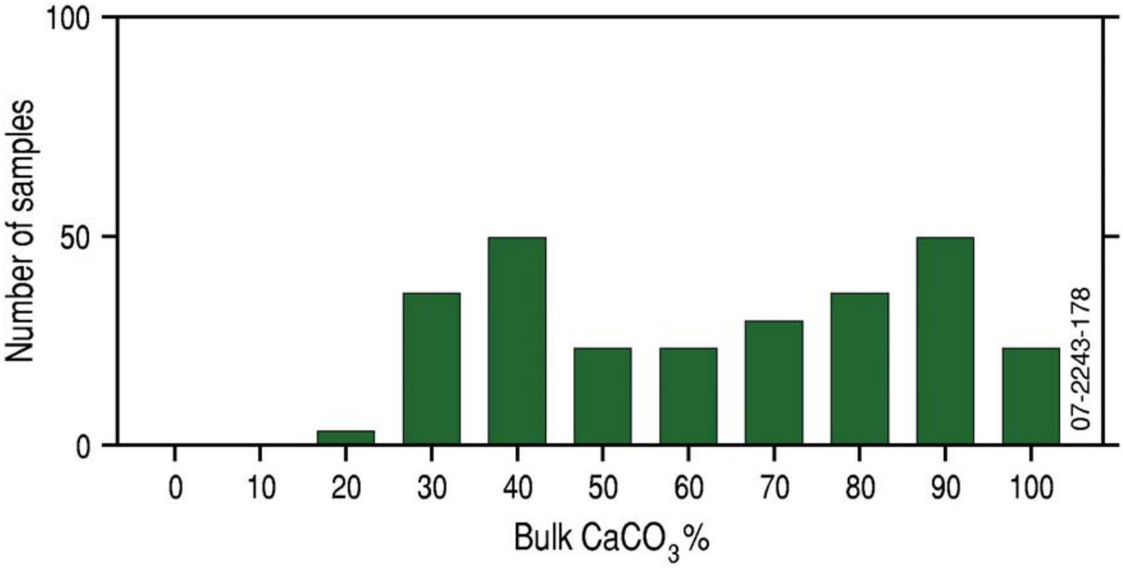
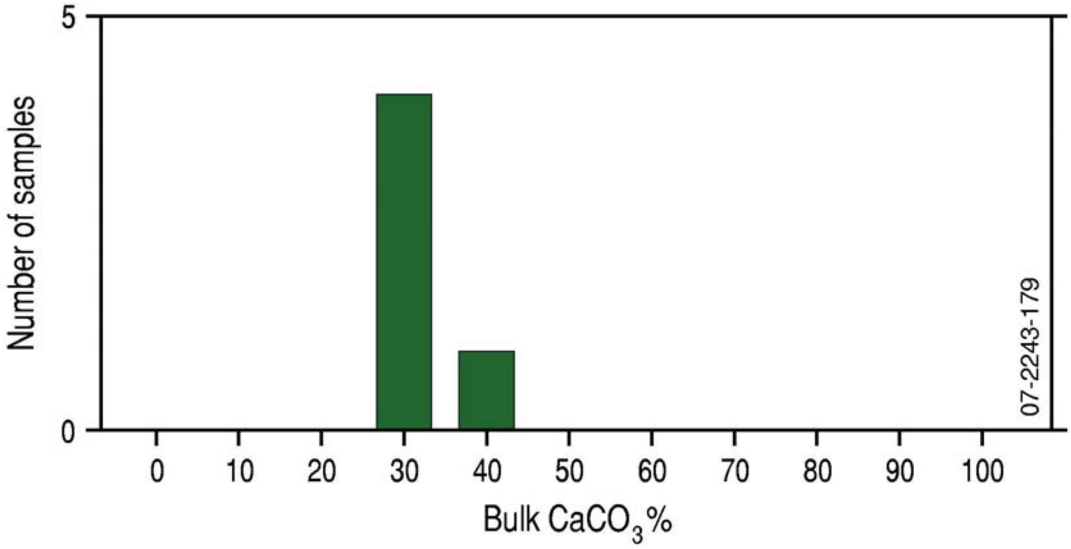


Figure 4.27. Texture (mud:sand:gravel ratio) of sediment in the NNMR.

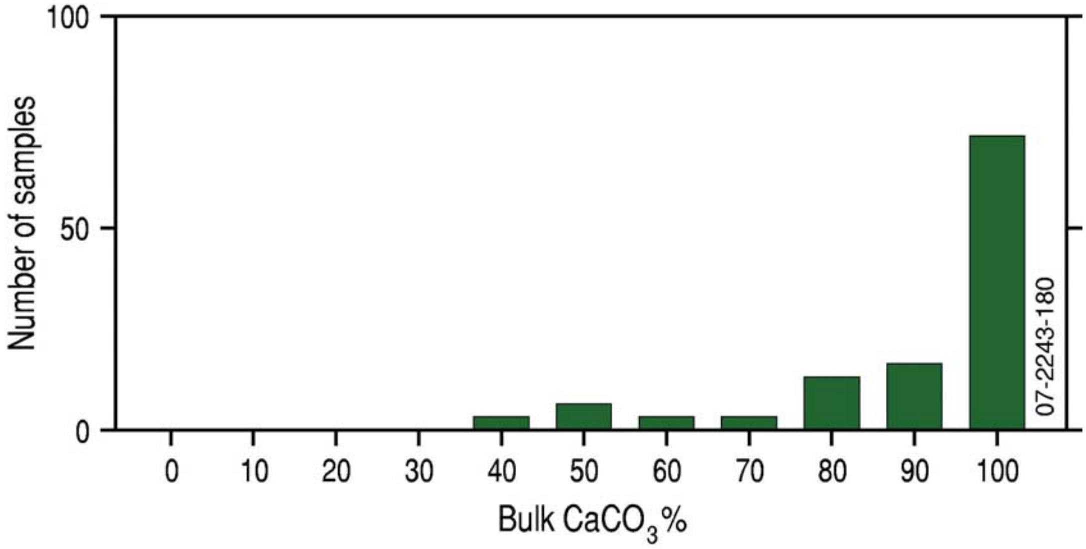
a)



b)



c)



d)

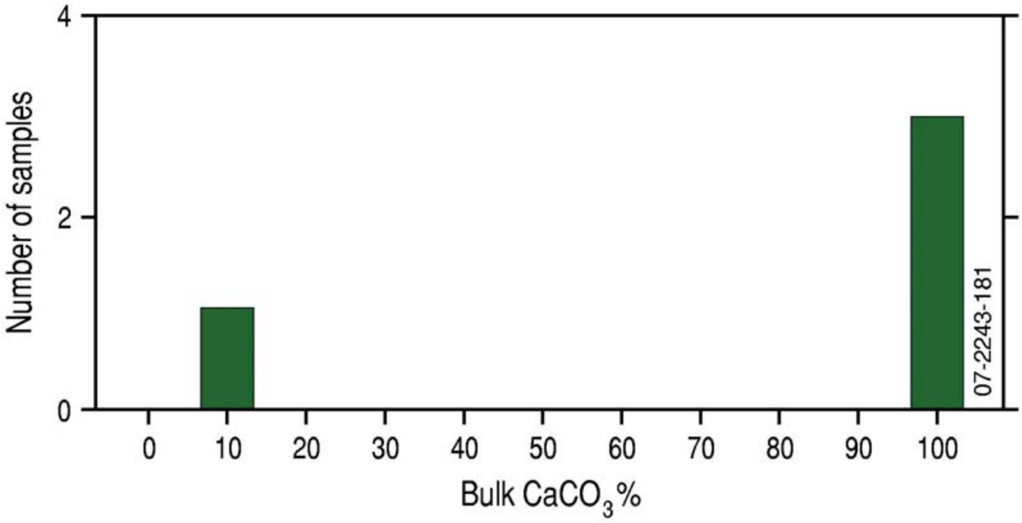
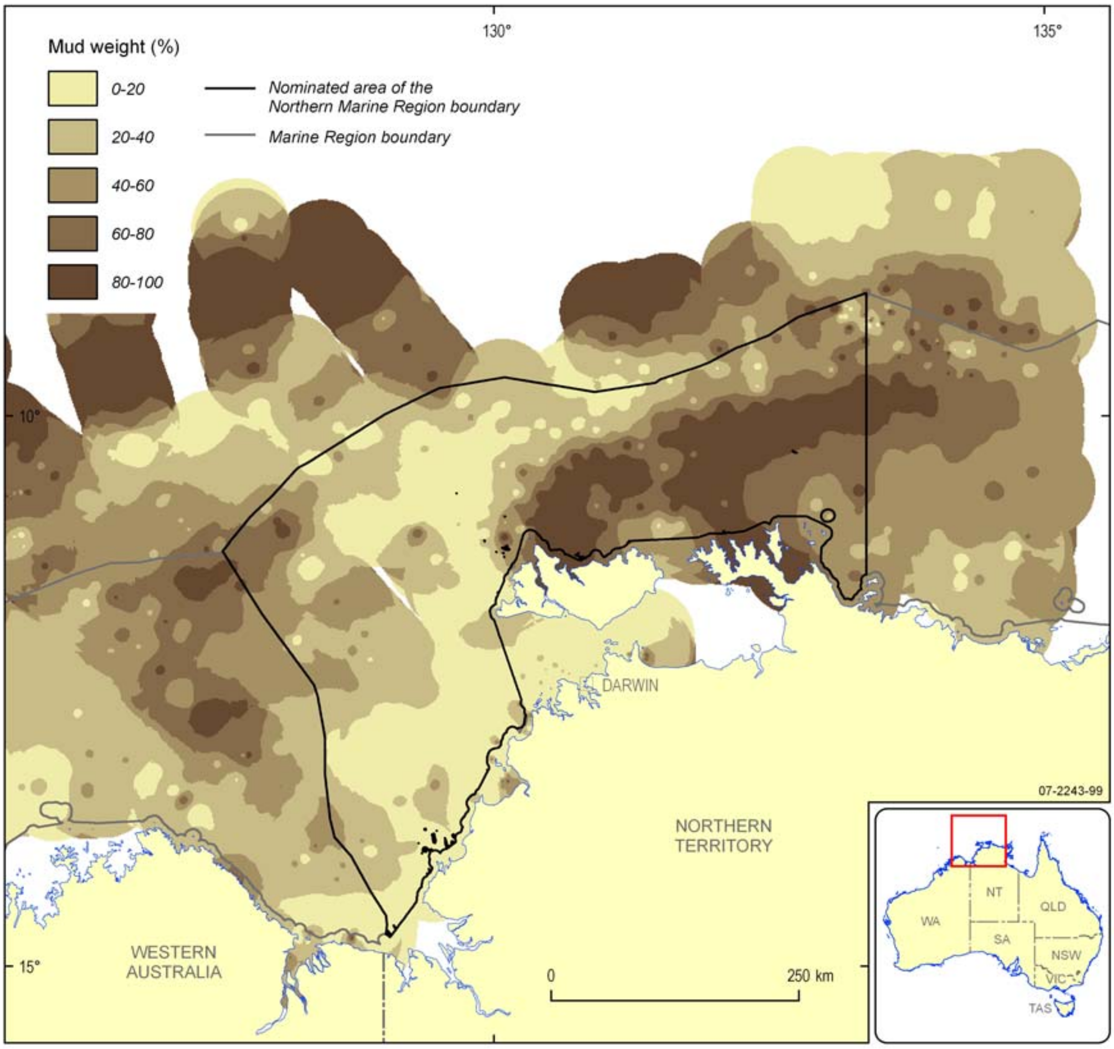


Figure 4.28. Carbonate content of NNMR sediment: a) bulk; b) mud; c) sand; and d) gravel.



a)

b)

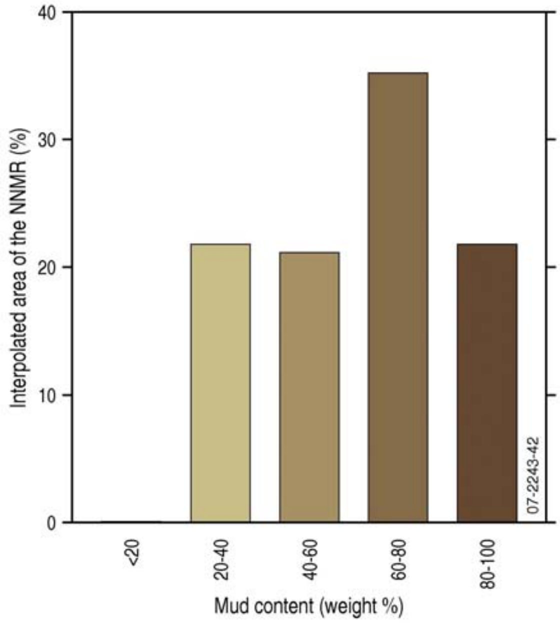
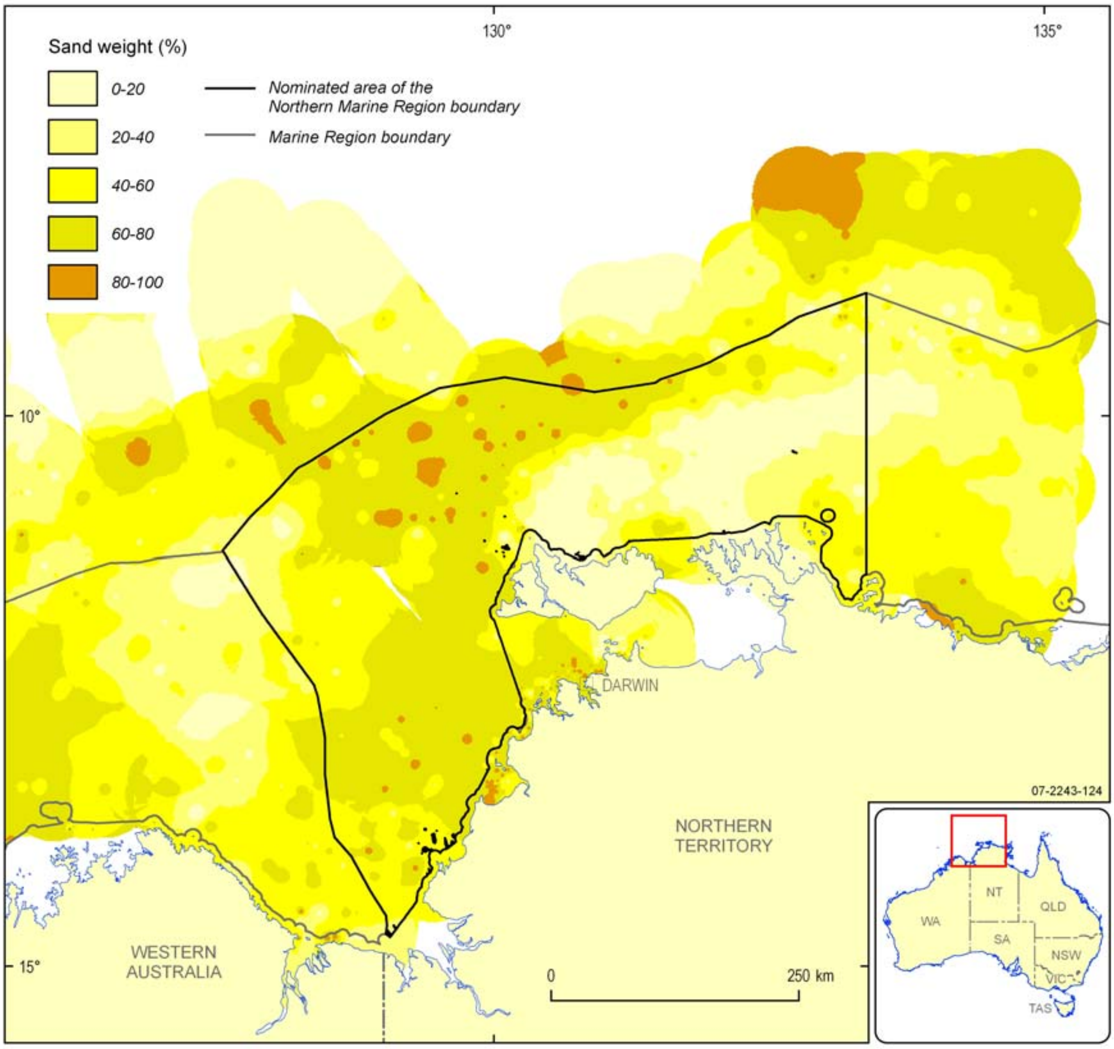


Figure 4.29. a) Mud distribution with b) the area covered by each class expressed as % of the interpolated area of the NNMR.



a)

b)

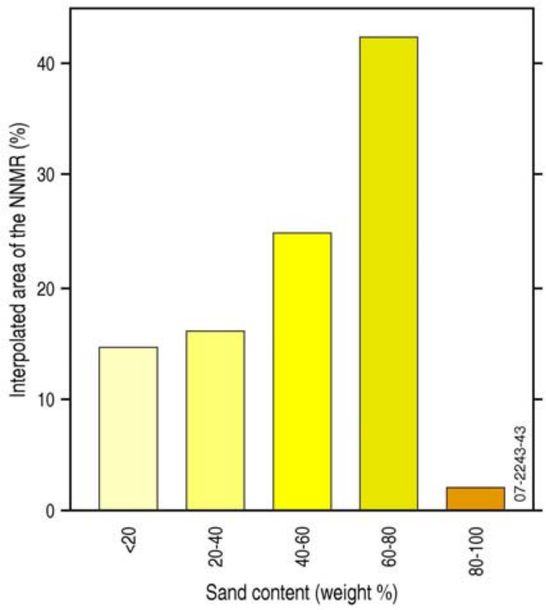
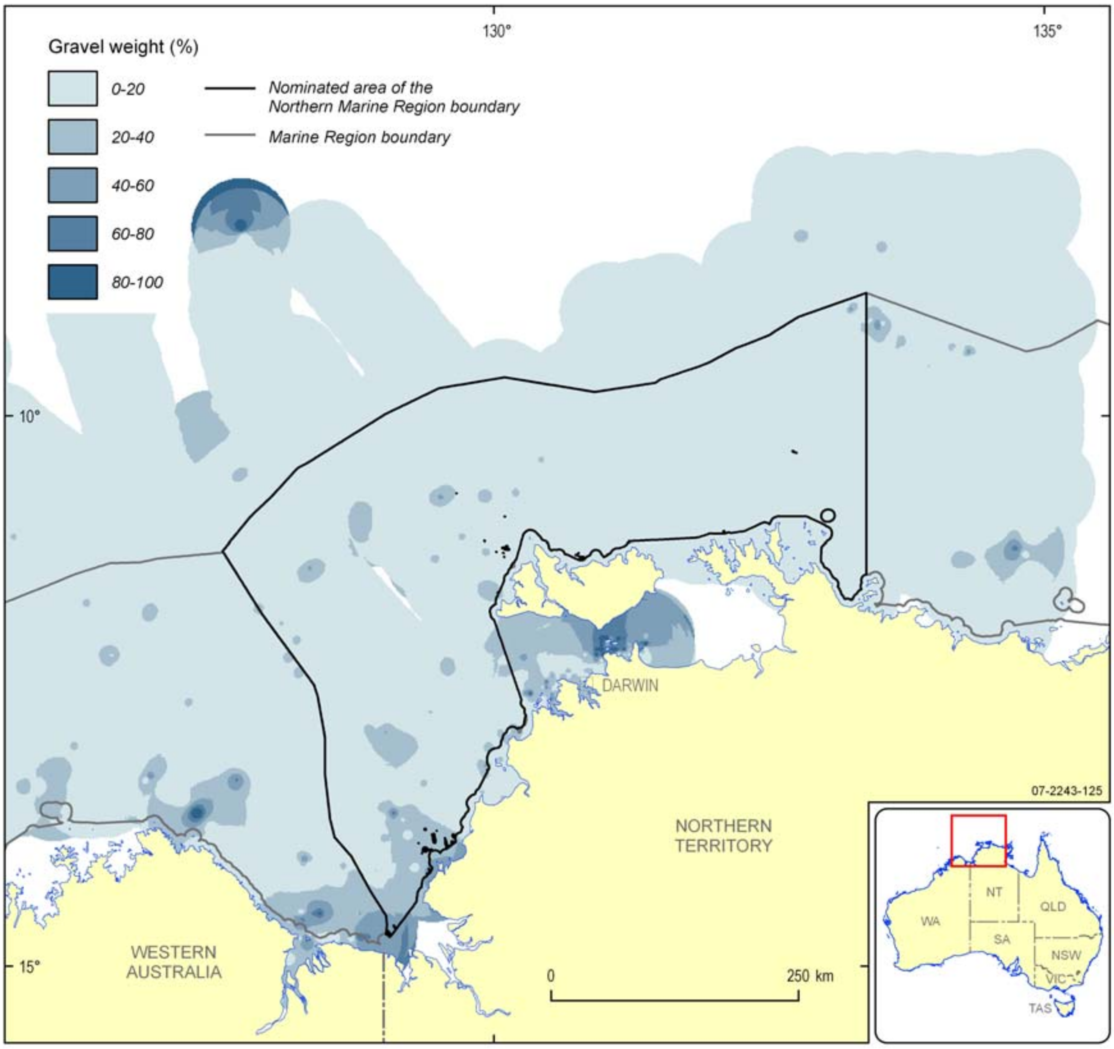


Figure 4.30. a) Sand distribution with b) the area covered by each class expressed as % of the interpolated area of the NNMR.

a)



b)

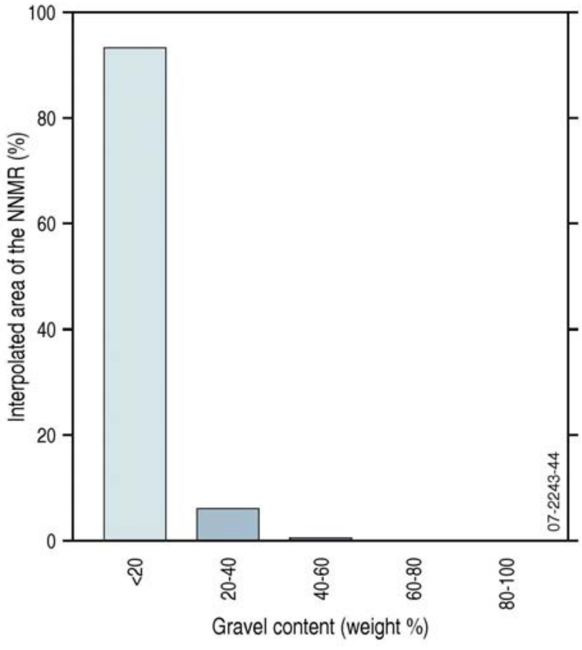
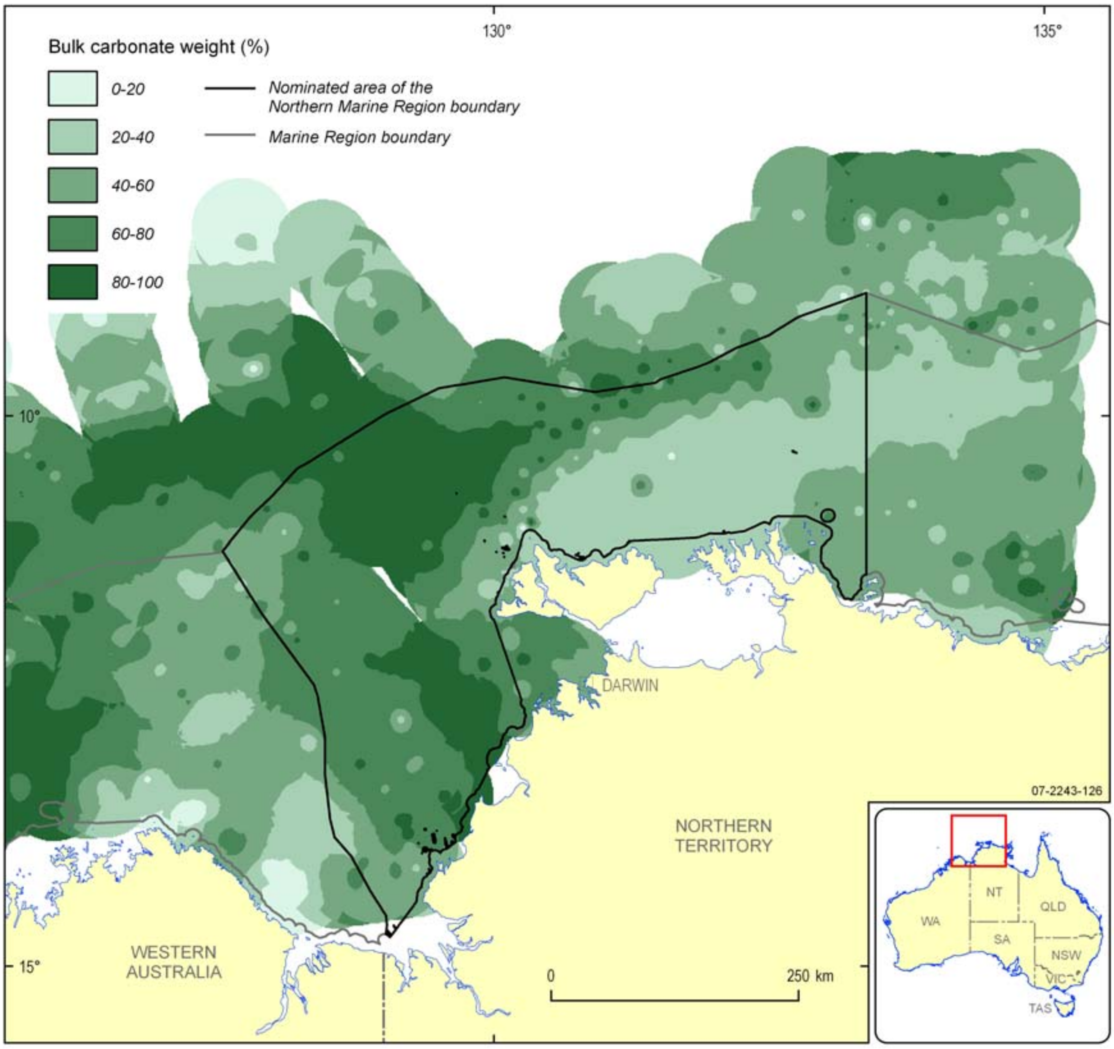


Figure 4.31. a) Gravel distribution with b) the area covered by each class expressed as % of the interpolated area of the NNMR.



a)

b)

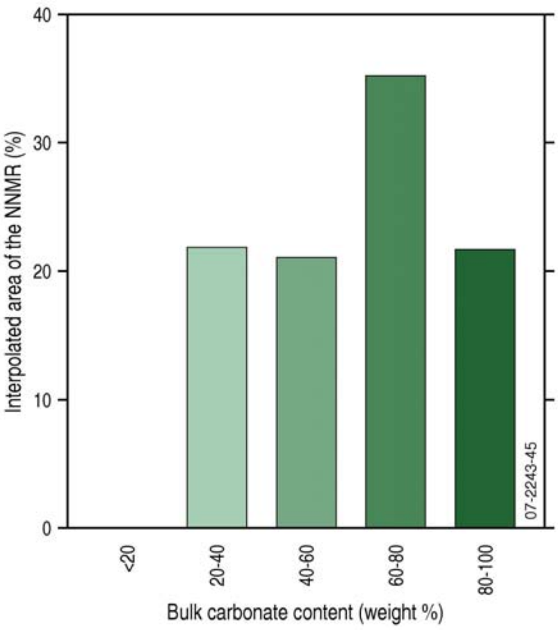
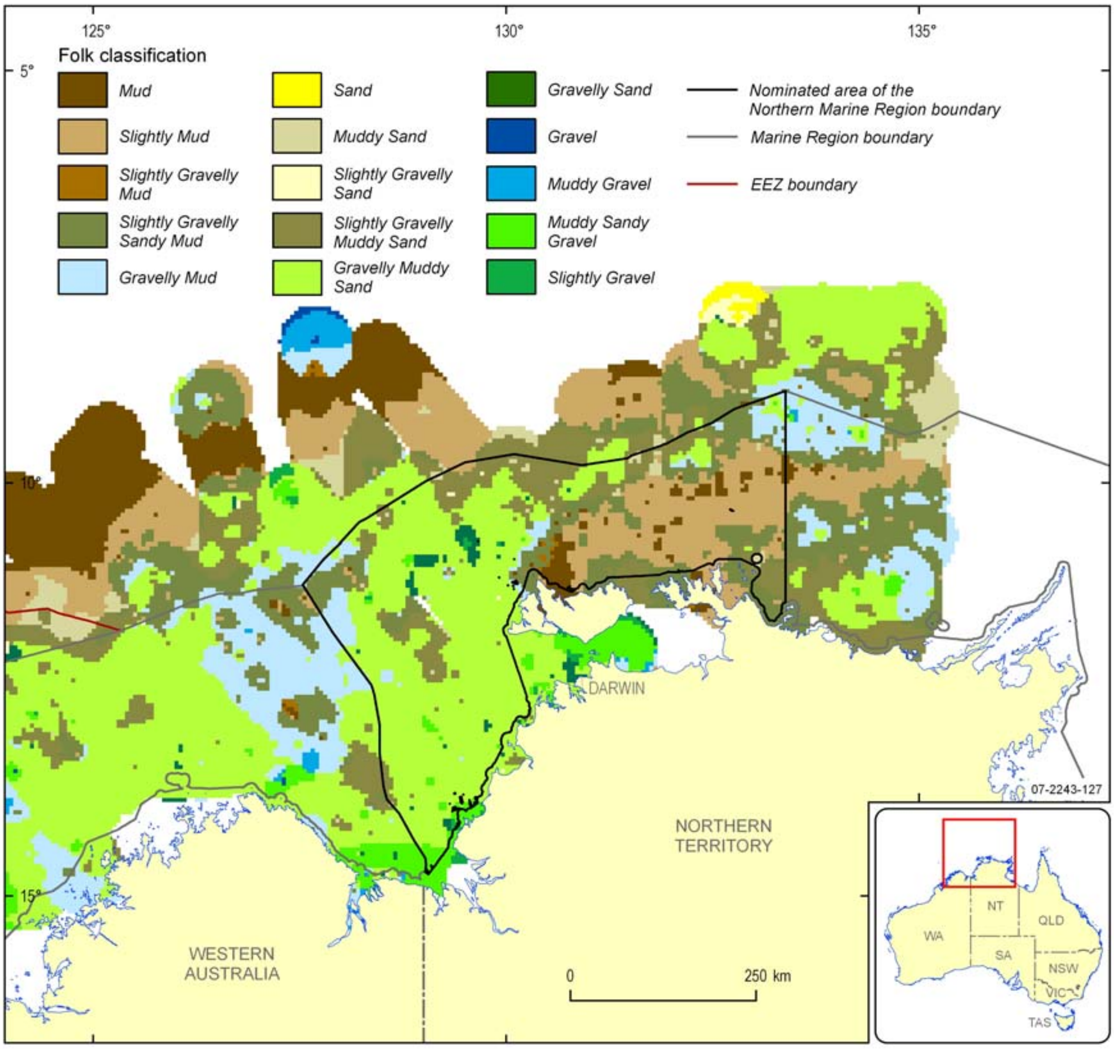
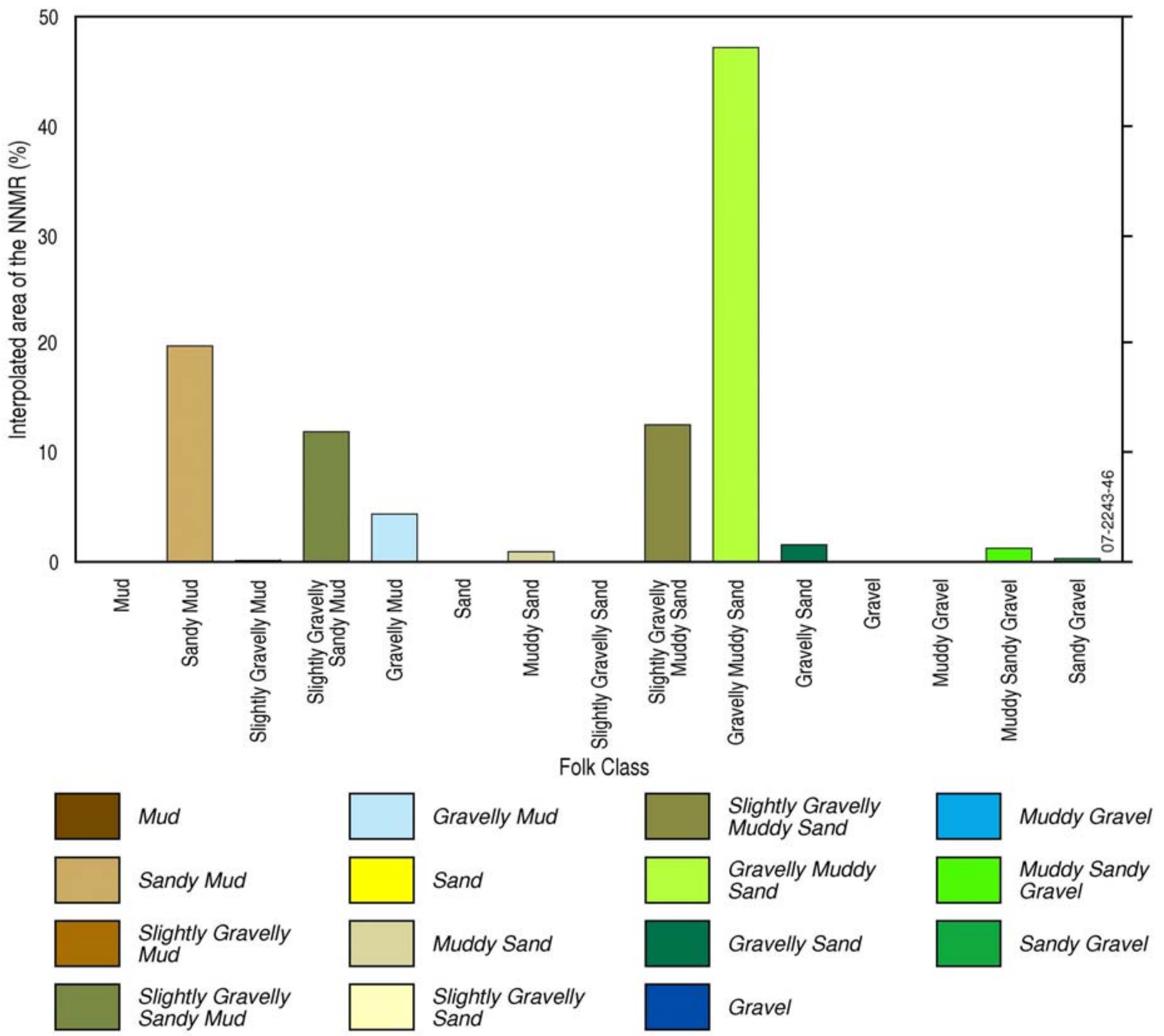


Figure 4.32. a) Bulk carbonate distribution with b) the area covered by each class expressed as % of the interpolated area of the NNMR.


125°
130°
135°
5°
10°
15°
Folk classification
Mud
Slightly Mud
Slightly Gravelly Mud
Slightly Gravelly Sandy Mud
Gravelly Mud
Sand
Muddy Sand
Slightly Gravelly Sand
Slightly Gravelly Muddy Sand
Gravelly Muddy Sand
Gravelly Sand
Gravel
Muddy Gravel
Muddy Sandy Gravel
Slightly Gravel
Nominated area of the Northern Marine Region boundary
Marine Region boundary
EEZ boundary
DARWIN
NORTHERN TERRITORY
WESTERN AUSTRALIA
0
250 km
07-2243-127
NT
QLD
WA
SA
NSW
VIC
TAS

a)



b)

Figure 4.33. Interpolated grainsize data displayed as Folk Classes with b) the area covered by each class expressed as % of the interpolated area of the NNMR.

4.2.4.2. Sedimentology of Geomorphic Provinces and Significant Features of the NNMR

Quantitative sedimentology is reported for features judged significant at a marine region scale and that attain adequate sample coverage. These features cover a large area of the NNMR, represent a relatively large percentage of the total area of this feature in the EEZ, or are judged to be unique to the NNMR based on physical properties such as area (km²) or water depth range. Where occurrences of a feature form distinct groups based on morphology or water depth, each group has been described separately. Where a feature is judged as significant, but does not attain adequate data coverage, features are noted as significant at a marine region or bioregion scale and properties and distribution of sediment within these features are, where possible, assessed from previous literature and summarised in Chapter 6.

Shelf Province

The shelf in the NNMR is represented by 268 grain size and 218 carbonate assays. The majority of the shelf to the west of Melville Island is sand dominated with localised deposits of gravel and/or mud (Figs 4.31a, 4.32a & 4.33a). The sedimentology of the shelf varies from east to west, with sand dominating the Sahul Shelf in the west of the NNMR and mud dominating the Arafura Shelf to the east. Sand content ranges from 0 to 94%, forming >50% of sediment volume in 148 samples (55%), and >80% in 35 samples (13%) (Fig. 4.34a). Mud content ranges from 0 to 100%, forming <40% of sediment in 143 samples (53%), and >90% in 36 samples (13%). Gravel content ranges from 0 to 68% and forms <20% of sediment volume in 235 samples (88%).

Samples with a high mud content (>60%) are restricted to the outer shelf and area north to north east of Melville and Bathurst Islands. Mud content on the shelf to the west of Melville and Bathurst Islands is generally <20%, and sand content ranges from 40 to 80%. Sediment containing >80% sand occurs locally on the Van Diemen Rise. Sediment containing >40% gravel is found in localised areas on the inner shelf in close proximity to the coast and to the west of Bathurst Island.

The carbonate content of shelf sediments in the NNMR is highest to the west of Melville and Bathurst Island (Fig. 4.35a). Carbonate content ranges from 8 to 99% and exceeds 75% in 75 shelf samples (35%). Samples with <30% carbonate occur on the middle shelf to the north of the Van Diemen Gulf. Carbonate sand content ranges from 28 to 100% in the 106 samples available samples, all of which are located to the west of Melville Island. Carbonate gravel content was not measured for existing samples from the shelf province.

Slope Province

The slope in the NNMR is represented by 45 grain size and carbonate assays. Sediment texture is zoned with water depth; accordingly, gravel and sand content decrease as mud content increases with water depth. Sand is the dominant size fraction across most of the slope comprising 0 to 91% of the sediment volume (Fig. 4.32a & 4.34b). A total of 27 samples (60%) contain >50% sand and six samples (13%) contain <10% sand. Mud content is highly variable, ranging from 2 to 100%, with 16 samples (36%) containing <20% mud and six samples (13%) containing >90% mud. Gravel content ranges from 0 to 59% and forms <10% of the sediment volume at 39 sites (87%) sampled. Gravel is abundant (20 – 60%) locally on the slope in the north east corner of the NNMR.

Carbonate content ranges from 19 to 88%, with 33 samples (73%) containing >50% carbonate and six samples (13%) containing <26% carbonate (Fig. 4.35b). The carbonate content of the sand fraction was measured for seven samples and exceeds 60% in six samples (86%). Carbonate content of the mud fraction was measured for five samples and ranges from 22 to 31% carbonate. Carbonate content of the gravel fraction was measured for four samples and attains 100% in all these samples.

Banks/shoals

A total of 13 grain size and nine carbonate assays were obtained from banks/shoals. Sand is the dominant fraction and ranges from 35 to 93%. A total of 11 samples (85%) contain >50% sand, and four samples (31%) exceed 85% sand (Fig. 4.36a). Gravel comprises from 1 to 43% of the sediment volume, and nine samples (70%) contain <20% gravel. Mud is less abundant, ranging from 0 to 43% with 10 samples (77%) containing <20% mud. Bulk carbonate ranges from 68 to 91%, and seven samples (78%) contain >90% carbonate. Carbonate sand was measured for nine samples and ranges from 97 to 100%, with eight samples (89%) attaining 100% carbonate sand (Fig. 4.37a). No carbonate mud or gravel contents were measured for existing samples in banks/shoals.

Deep/hole/valleys

A total of 12 grain size and nine carbonate assays were obtained from deeps/holes/valleys. Sand is the dominant fraction ranging from 35 to 94%, with 11 samples (92%) containing >50% sand and five samples (42%) exceeding 80% sand (Fig. 4.36b). Mud is the next most abundant fraction, ranging from <1 to 39%, with nine samples (75%) containing <30% mud. Gravel content ranges from 3 to 37% and is <15% in nine samples (75%). Bulk carbonate content ranges from 68 to 96% and exceeds 70% in eight samples (67%) (Fig. 4.37b). Carbonate content of sand is consistently high, ranging from 81 to 100% in five samples (100%). No carbonate mud or gravel contents were measured for existing samples in deeps/holes/valleys.

Basins

A total of 31 grain size and 28 carbonate assays were obtained from basins. Mud and sand are the dominant fractions ranging from 11 to 93% and from 55 to 79%, respectively (Fig. 4.36c). Mud content is variable with 24 samples (70%) containing <50% mud and two samples (7%), located on the eastern flank of the Bonaparte Depression, containing >85% mud. Mud is less abundant in basins near the shelf break, ranging from 11 to 29%. Sand content ranges from 7 to 79% with 19 samples (61%) containing 50 to 80% sand. Gravel forms <10% in 16 samples (51%) and is absent in four samples (13%). Bulk carbonate content ranges from 38 - 87% with 26 samples (84%) exceeding 50% carbonate (Fig. 4.37c). Carbonate content of sand is consistently high, ranging from 76 to 100% and attaining 100% in nine samples (29%). No carbonate mud or gravel contents were measured for existing samples in basins.

Canyons

A total of four grain size and carbonate assays were obtained from two adjacent canyons located on the slope. Mud is the most abundant fraction of these samples and ranges from 35 to 58% with three samples (75%) containing >50% mud (Fig. 4.36d). Sand is the next most abundant fraction, ranging from 38 to 65%, with three samples (75%) containing <50% sand. Gravel does not exceed 7% of sediment volume and is absent from two samples (50%). Bulk carbonate content ranges from 39 to 57%, with three samples (75%) containing 50 to 57% carbonate (Fig. 4.37d). Carbonate content was not measured for any of the grain size fractions.

Ridges

A total of five grain size and carbonate assays were obtained from ridges. Sand is the most abundant fraction ranging from 9 to 86%, however four of these samples (80%) contain >67% sand. Gravel is the next most abundant size fraction ranging from 0 to 25%, with three samples (60%) containing >10% gravel (Fig. 4.36e). Mud content is generally low, ranging from 2 to 9% in four samples (80%), but it exceeds 90% in one sample adjacent to an apron/fan feature. Bulk carbonate content ranges from 19 to 82% and exceeds 50% in three samples (60%) (Fig. 4.37e). Carbonate content of the sand fraction was measured for three samples and ranges from 71 to 88%. Carbonate content of the mud fraction was measured for one sample and this attains 23%. All gravel fractions were composed entirely of carbonate.

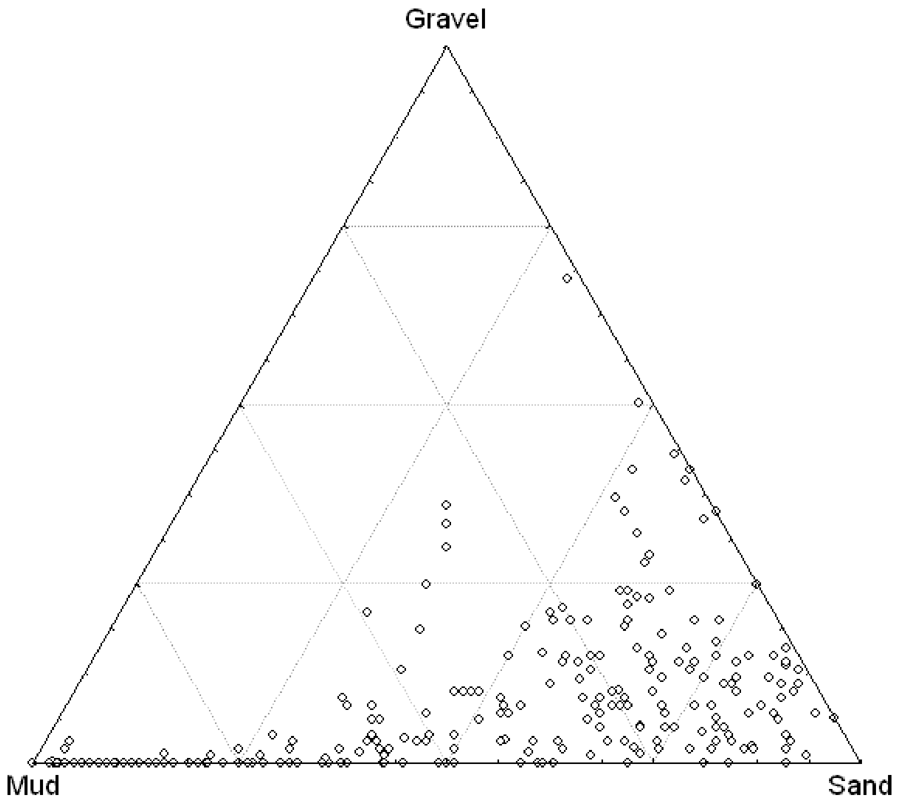
Aprons/fans

A total of 10 grain size and carbonate assays were obtained from aprons/fans. Mud is the dominant fraction, ranging from 9 to 100% with eight samples (80%) containing >50% mud (Fig. 4.36f). Sand contents range from 2 to 80%, although eight samples (80%) contain <35% sand. Gravel generally ranges from 0 to 5% and is absent in four samples (40%)(40%), however one sample located adjacent to a ridge contains 59% gravel. Bulk carbonate content ranges from 23 to 67% and eight samples (80%) contain <50% carbonate (Fig. 4.37f). Carbonate content of the sand fraction was measured for two samples and ranges from 49 to 64%. Carbonate mud was measured for four samples and ranges from 22 to 31%. No carbonate gravel contents were measured for existing samples in aprons/fans.

Terraces

A total of 40 grain size and 38 carbonate assays were obtained from terraces. Sand is the dominant fraction and ranges from 21 to 90%. A total of 32 samples (80%) contain >50% sand, and eight samples (20%) contain >80% sand (Fig 4.36g). Mud content is variable, ranging from 4 to 78% with 30 samples (75%) containing <40% mud and five samples (13%) containing >60%. Gravel content is <16% in 38 samples (95%). Two samples (5%) contain approximately 22% gravel, displaying similar properties to sediments found in adjacent banks/shoal features. Bulk carbonate content ranges from 43 to 98% and exceeds 50% in 35 samples (92%) and 85% in 11 samples (29%) (Fig. 4.37g). Carbonate content of the sand fraction was measured for 23 samples and ranges from 43 to 100% with 18 samples (78%) exceeding 95%. No carbonate mud or gravel contents were measured for existing samples in terraces.

a)



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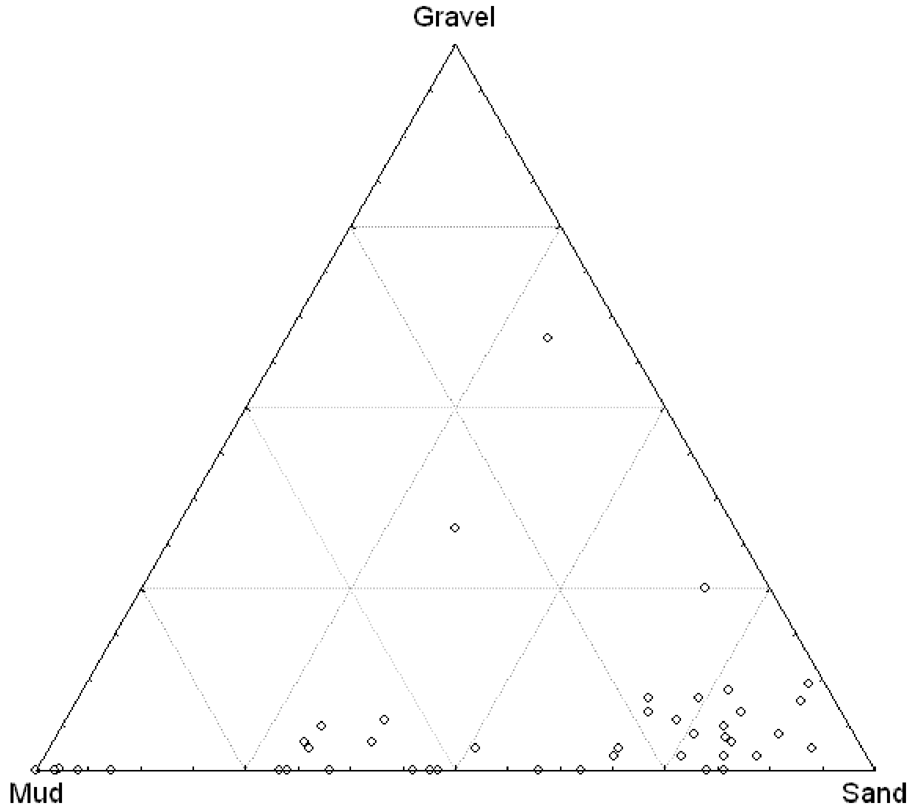
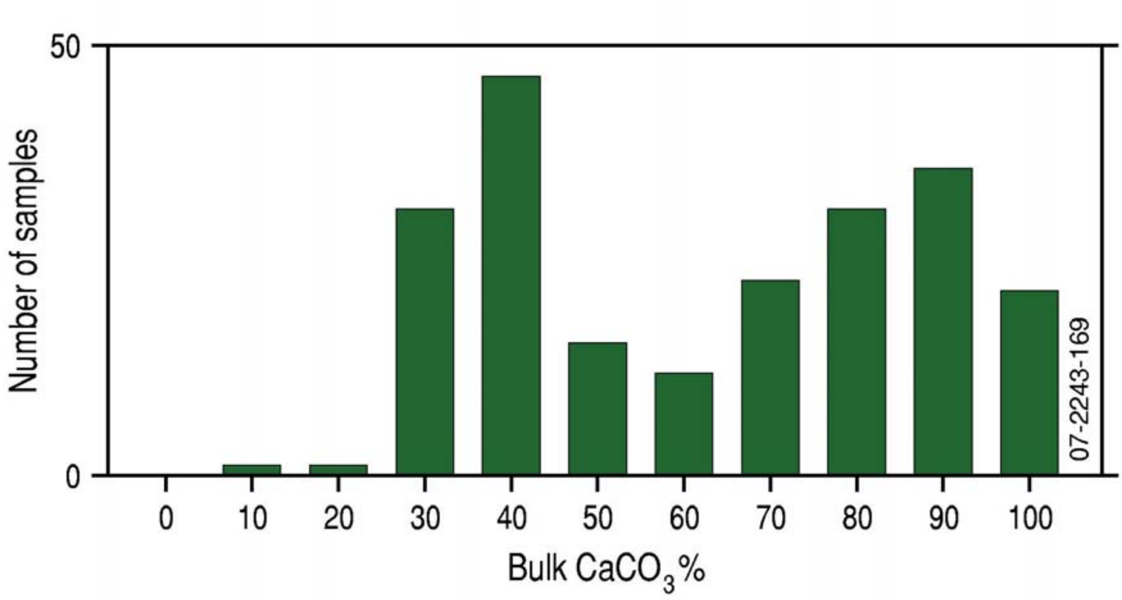


Figure 4.34. Texture of sediment in geomorphic provinces: a) shelf & b) slope of the NNMR.

a)



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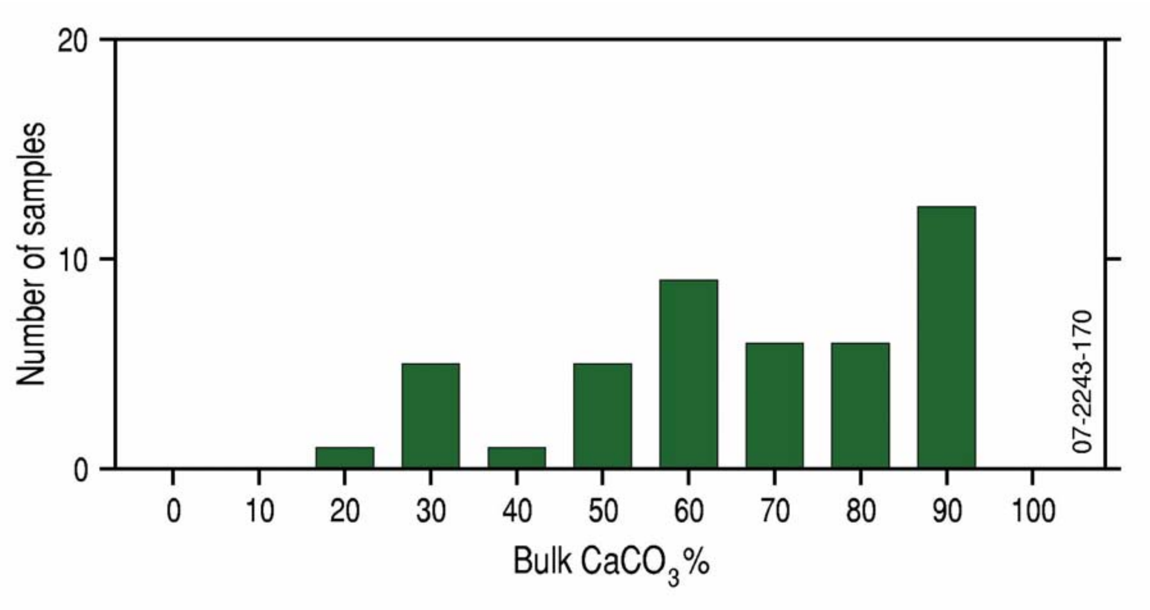
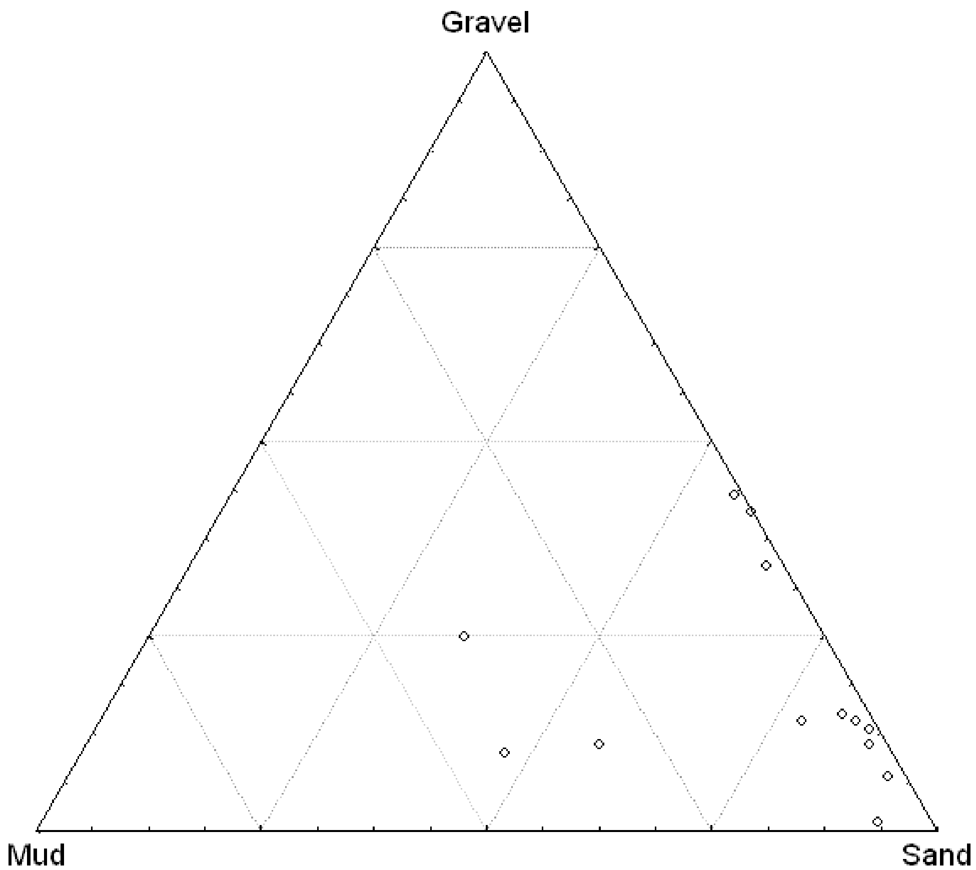
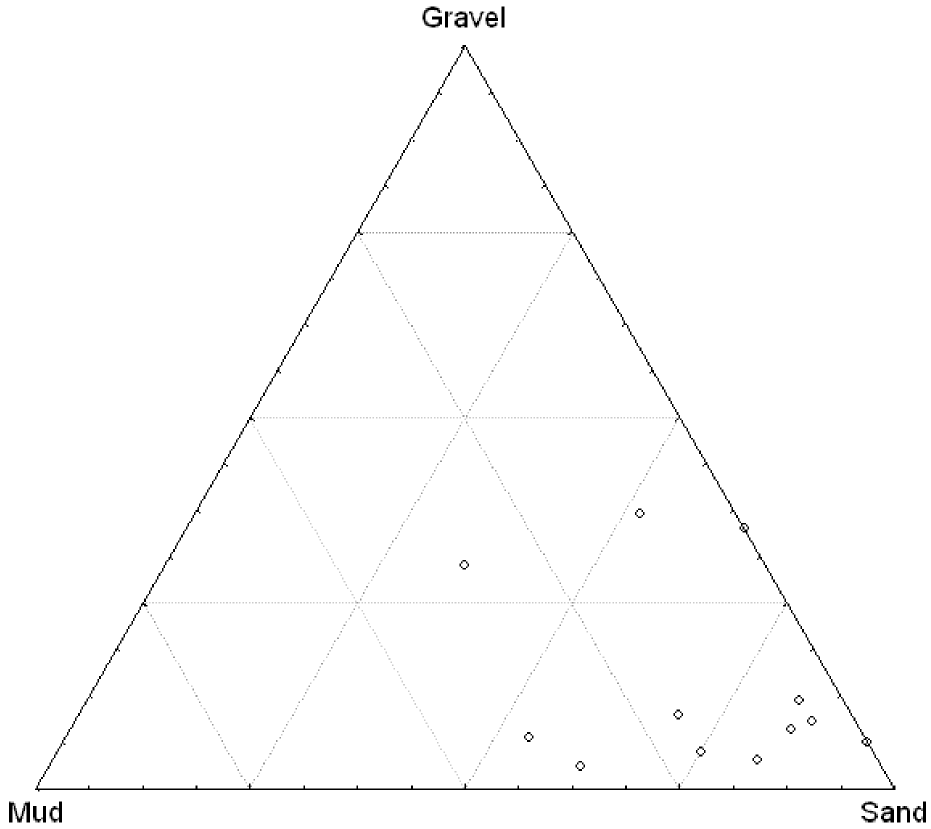


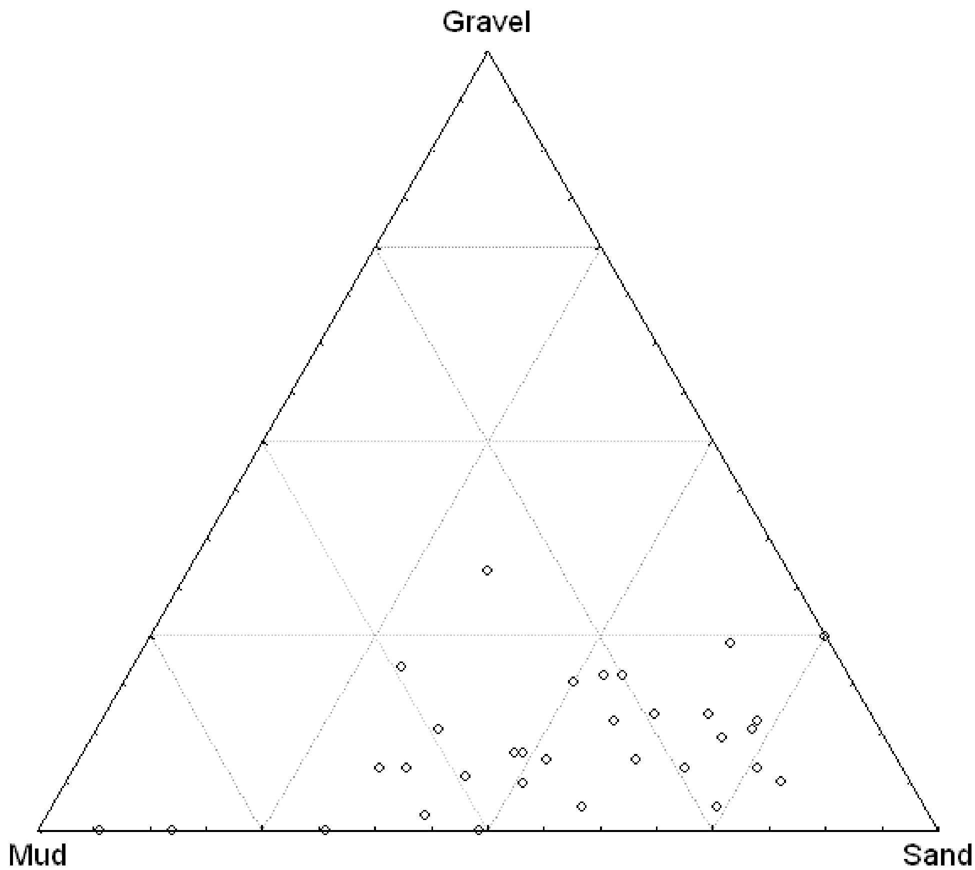
Figure 4.35. Bulk carbonate content of geomorphic provinces: a) shelf & b) slope of the NNMR.



a)

b)





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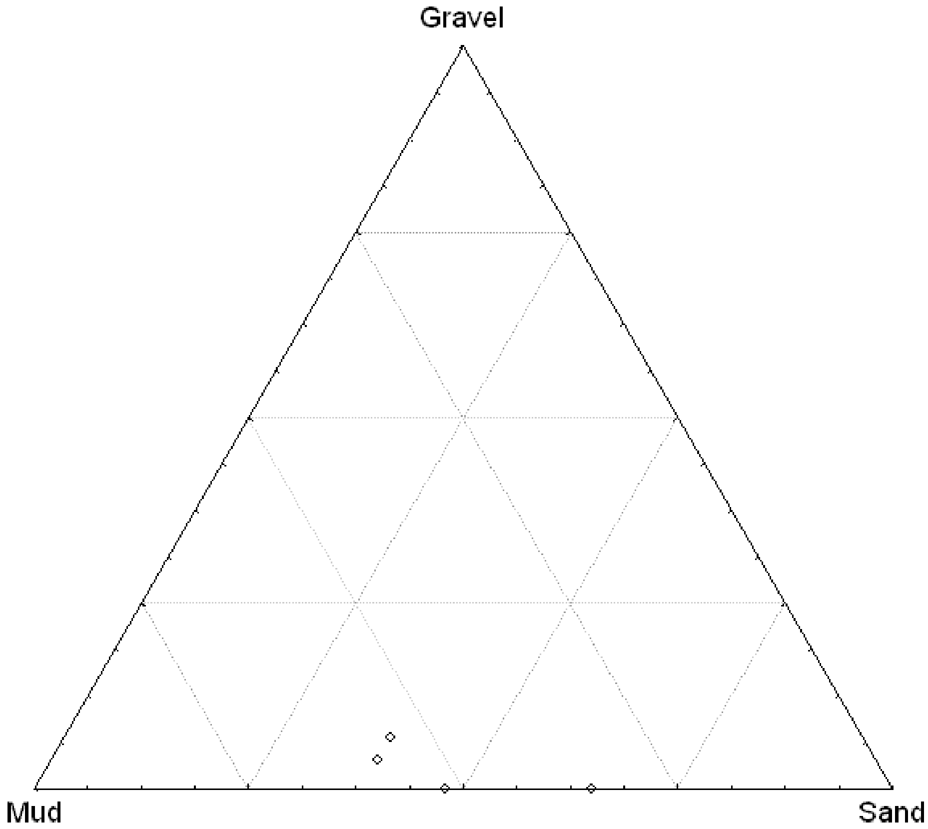

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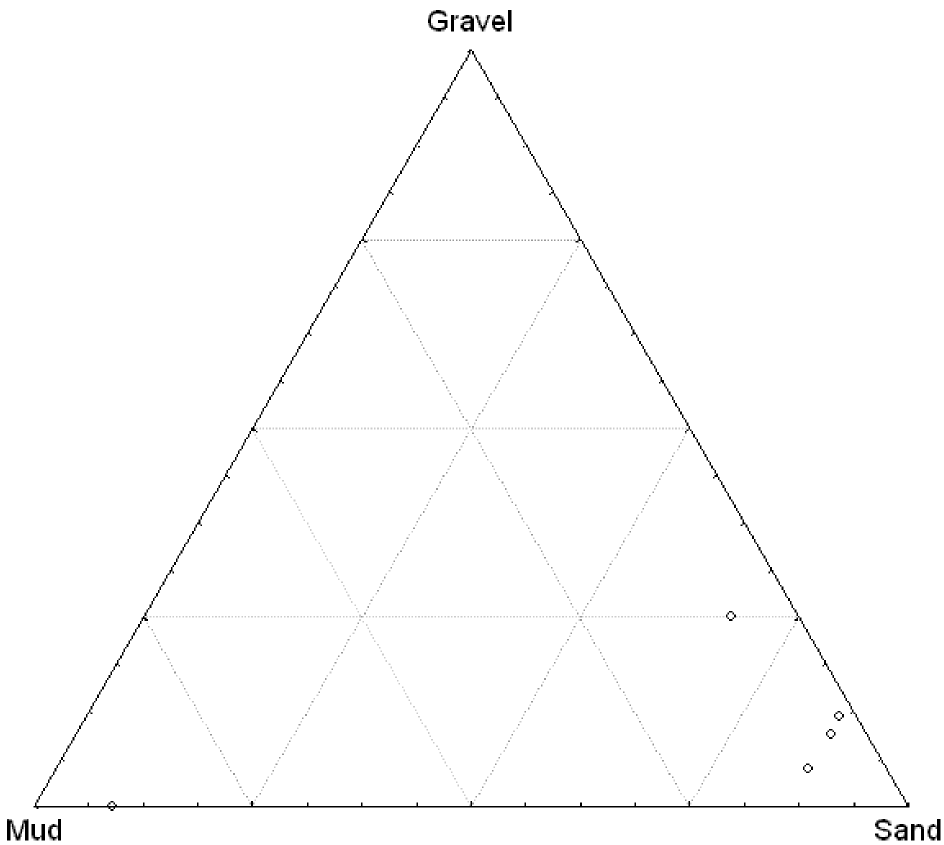

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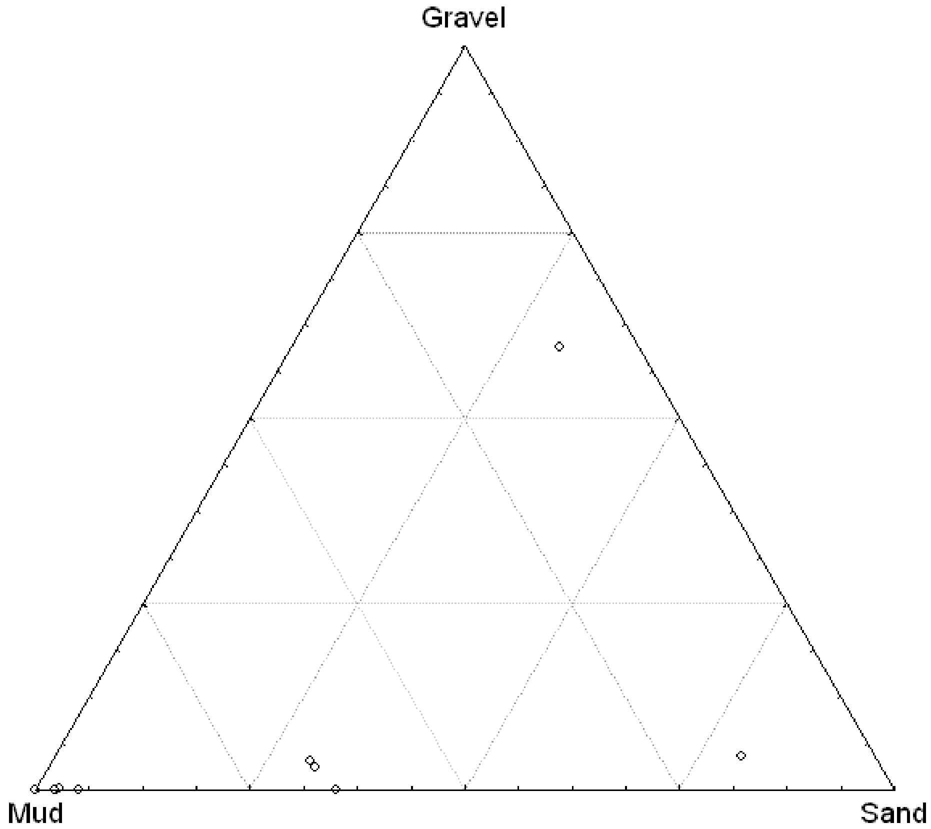
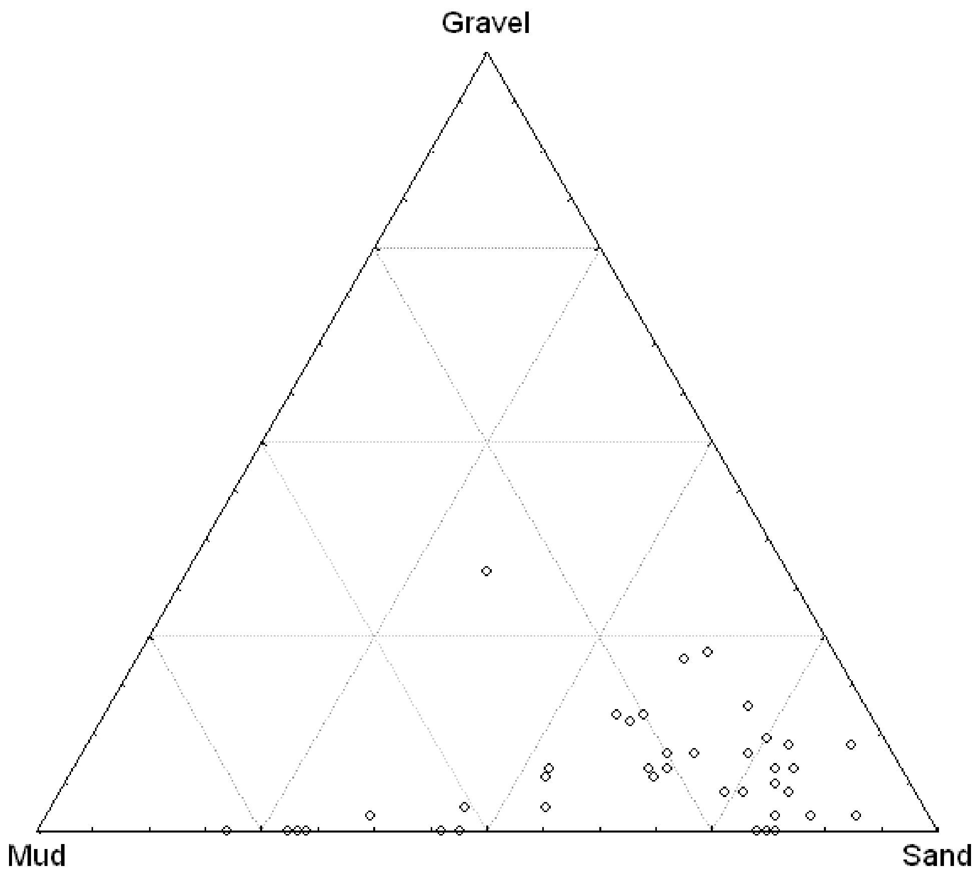
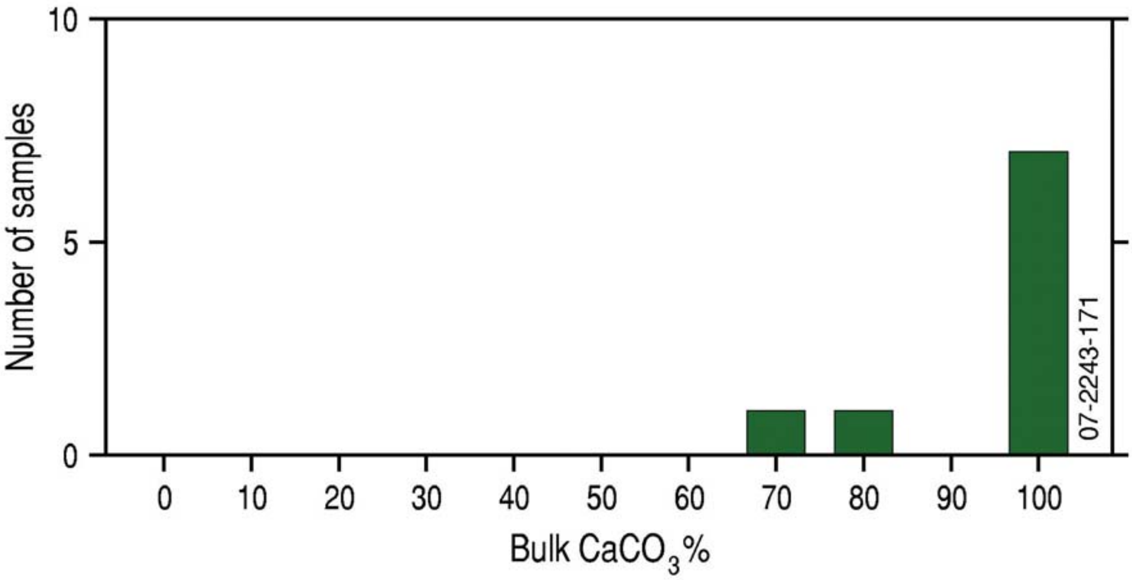




g)

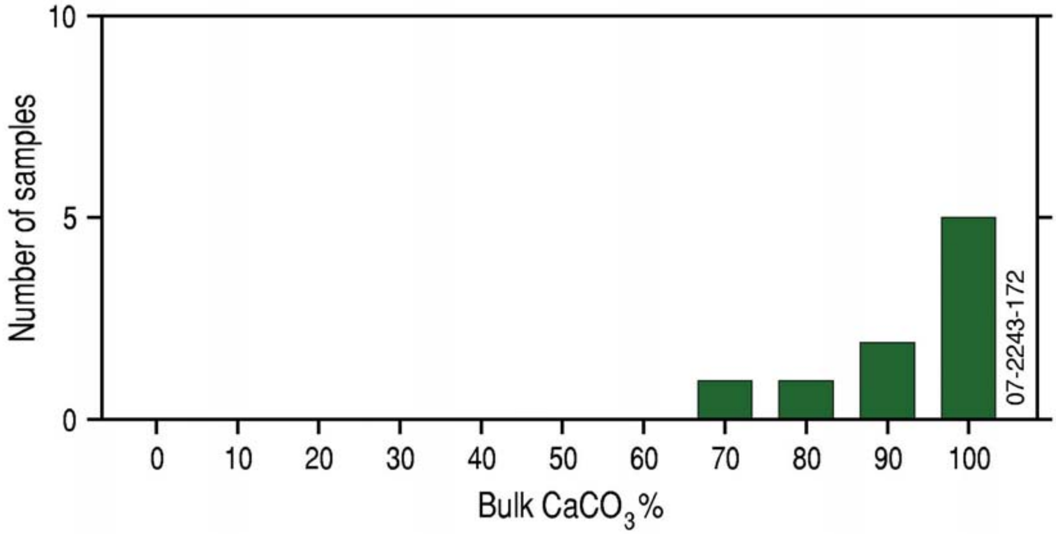
Figure 4.36. Textural composition (mud:sand:gravel ratio) of geomorphic features in the NNMR: a) bank/shoal; b) deep/hole/valley; c) basin; d) canyon; e) ridge; f) apron/fan; and g) terrace.

a)



10
5
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-171

b)



10
5
0
Number of samples
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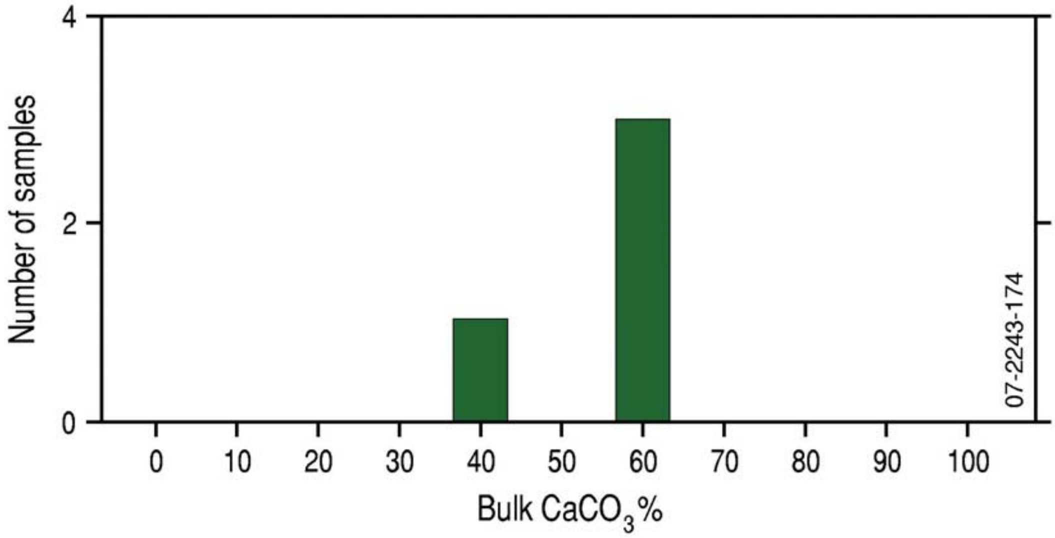
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-172

c)


Number of samples
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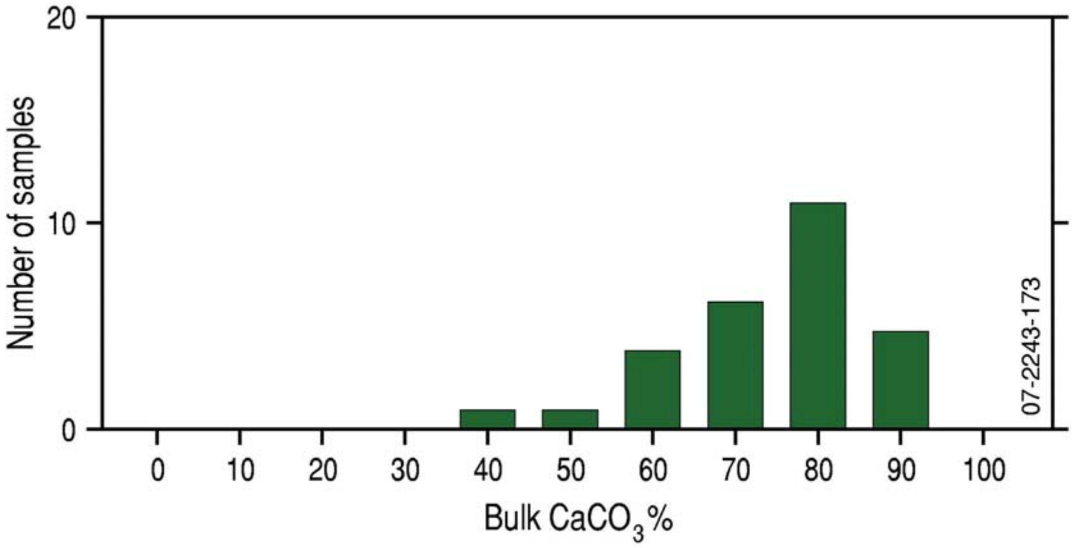
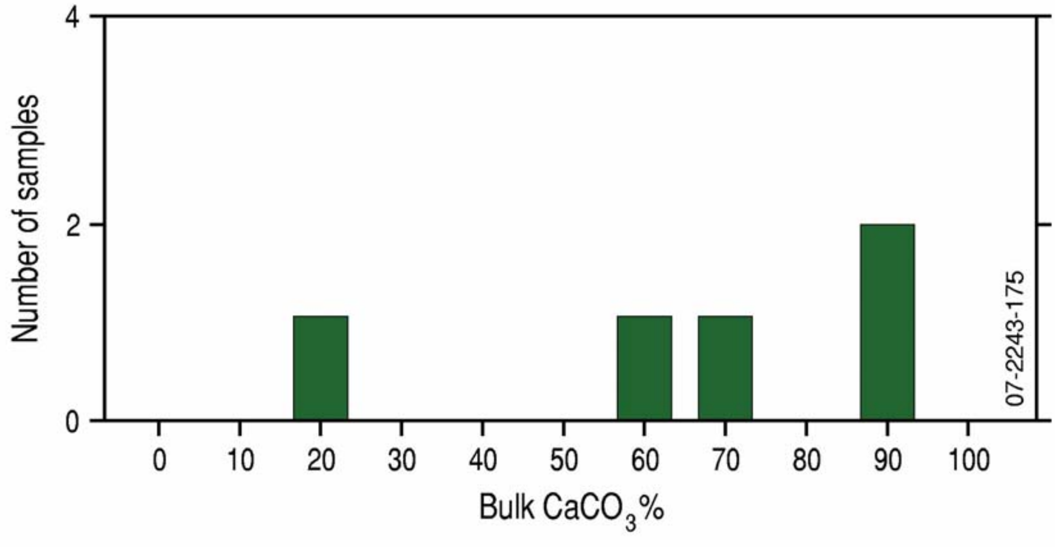
2
4
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-174

d)


Number of samples
0
10
20
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-173

e)


Number of samples
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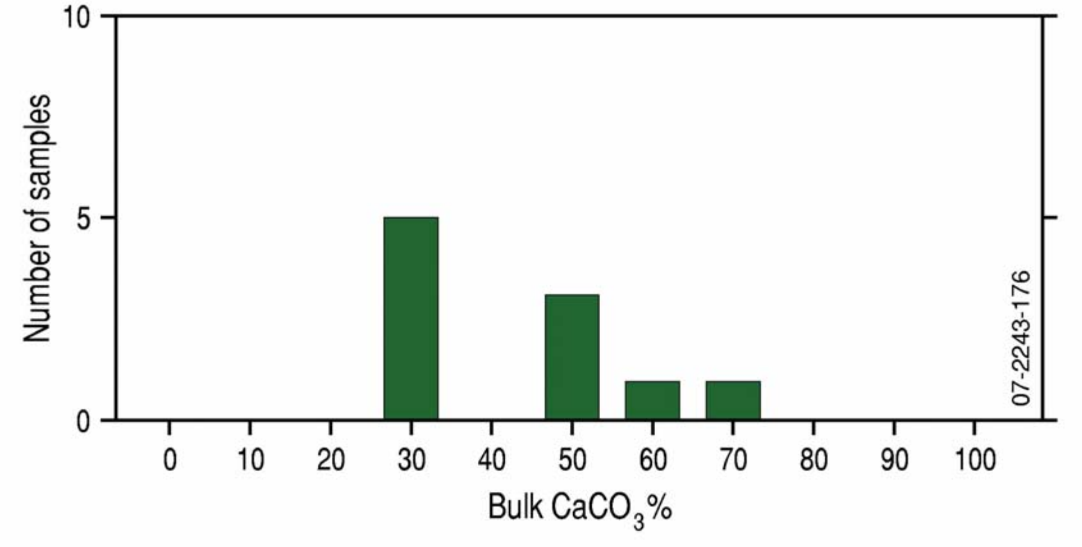
2
4
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-175

f)



g)

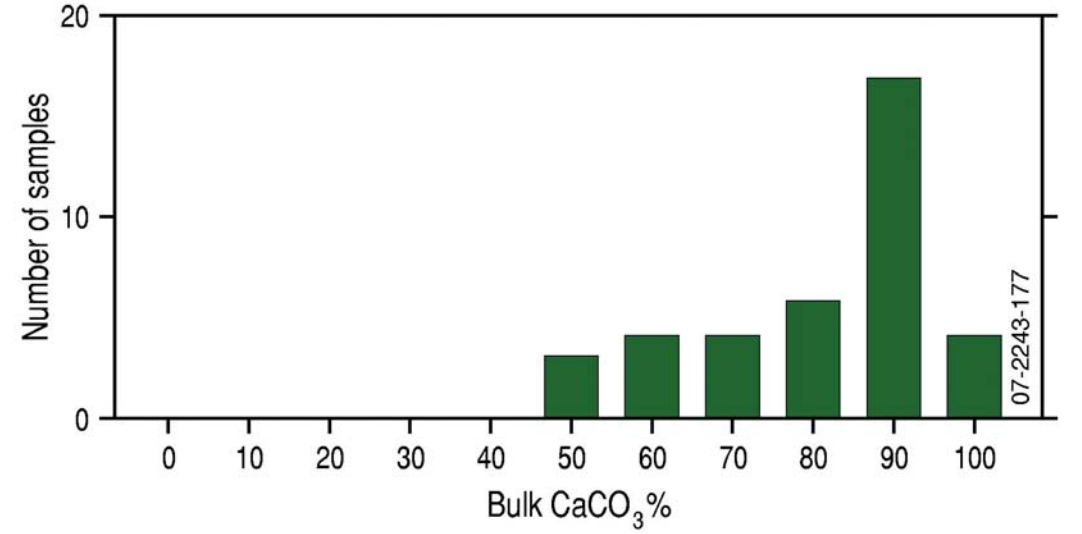


Figure 4.37. Composition of bulk carbonate content in geomorphic features of the NNMR: a) bank/shoal; b) deep/hole/valley; c) basin; d) canyon; e) ridge; f) apron/fan; and g) terrace.

5. Geomorphology and Sedimentology of Bioregions

5.1 INTRODUCTION

Samples with quantitative textural and compositional data represent all eight bioregions in the NWMR (Fig. 5.1; Table 5.1). New data significantly improve sample densities in seven of the eight bioregions and provide the first sediment data for the Central Western Shelf Transition in the NWMR.

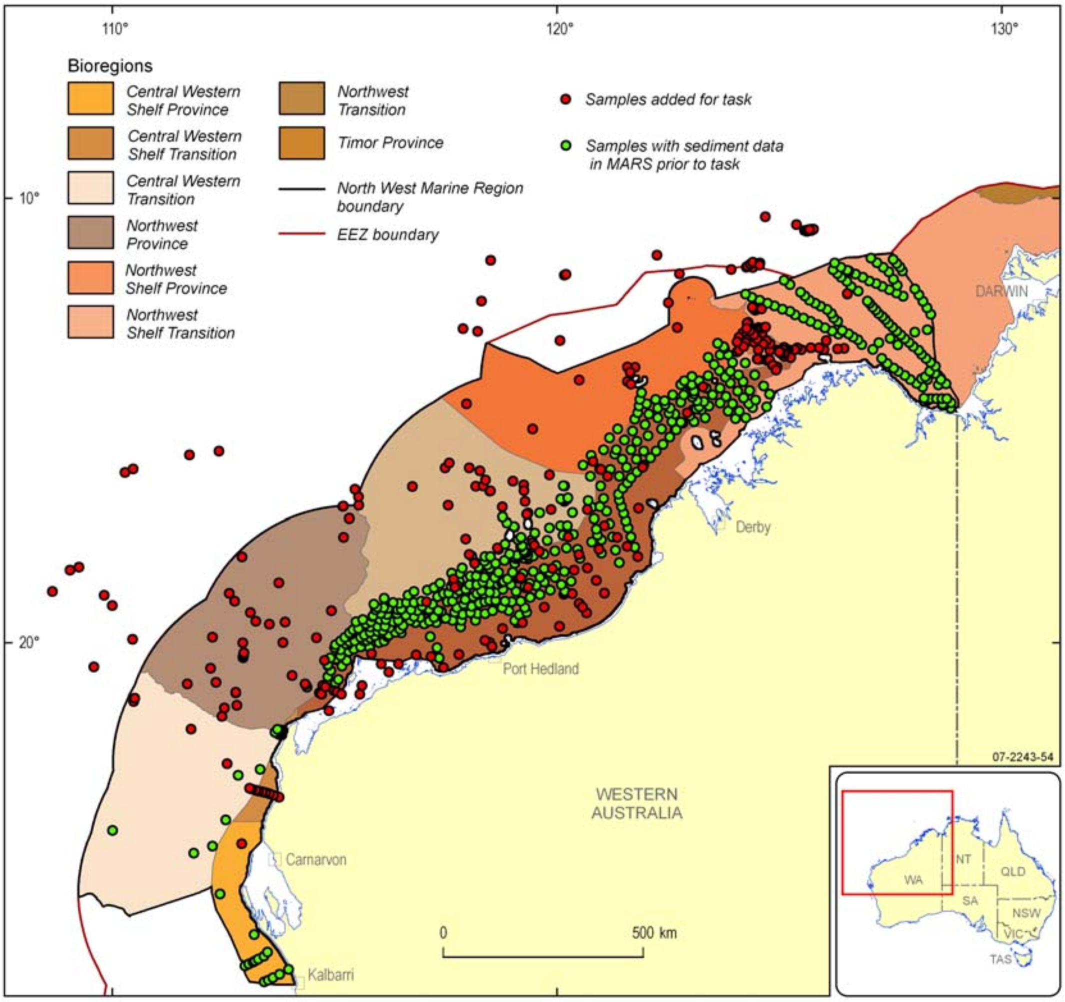
A total of 693 samples (72%) occur in the four shelf bioregions which comprise <37% of the NWMR area. A total of 275 samples (28%) occur in the four offshore bioregions which comprise 64% of NWMR area. The remaining 17 (1%) samples occur in the area of the NWMR not allocated to any bioregion. Data added from the current study 120 samples in shelf bioregions and 115 samples in offshore bioregions.

Average sample densities attain >1:2,550 km² in four Shelf and two offshore bioregions (Table 5.1). Elsewhere in the NWMR average sample densities are lower. The Northwest Province (NWP) covers 178,700 km² or 17% of the NWMR and contains 58 samples; this results in an average sample density of <1:3,100 km². The Central Western Transition (CWT) covers 162,900 km² or 15% of the NWMR and contains 15 samples, resulting in a sample density of <1:10,850 km² (Table 5.1).

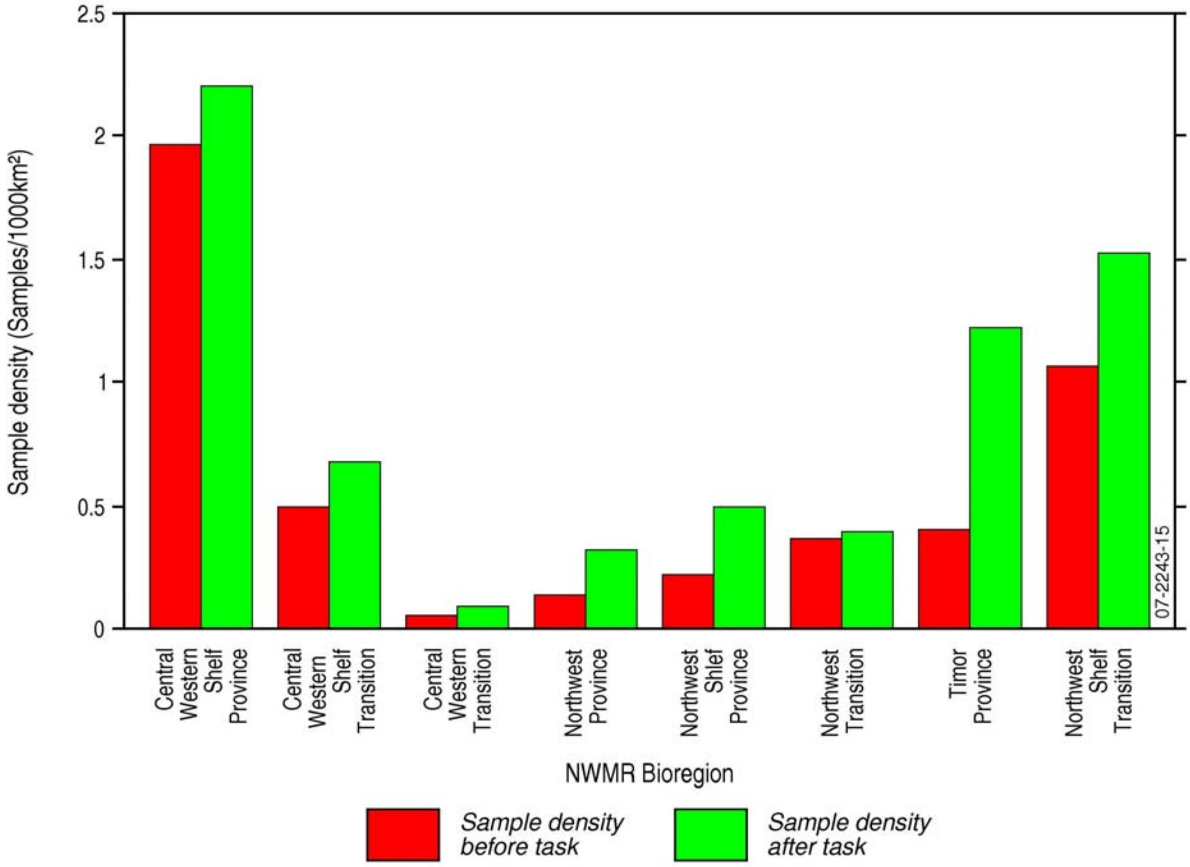
Geomorphology and bathymetry of each bioregion is described from quantitative data (Chapter 4). Where sample coverage is adequate, the sedimentology of geomorphic features judged to be significant within each bioregion is described. The Central Western Shelf Province (CWSP), Central Western Shelf Transition (CWST) and much of the Northwest Shelf province (NWSP) are characterised by simple geomorphology and data coverage is adequate to describe the sedimentology of most features. Where bioregions are characterised by complex geomorphology, particularly the Northwest Shelf Transition (NWST), data coverage is insufficient to describe the sedimentology of all the geomorphic features. Where available, information from previous studies (Chapter 3) and from the planning region scale analysis (Chapter 4) are used to characterise seabed sediments in features without sufficient sample coverage for analysis at bioregion scales. This information is included in the summary and discussion of results in Chapter 6.

Shelf and offshore bioregions can be distinguished from one another based on sediment texture and composition and the spatial distribution of these properties relative to other physical data sets such as bathymetry and geomorphology. Changes in sedimentology are most clearly observed by an increase in mud content and decrease in carbonate of sediment within offshore bioregions compared to shelf bioregions (Fig. 5.2 & 5.3). 79% (a total of 417 samples) of samples in shelf bioregions contain >80% carbonate content compared to 60% (154 samples) in the offshore bioregions. Similarly, 21% (225 samples) of samples in offshore bioregions contain >80% mud content compared to only 3% (14 samples) of samples in shelf bioregions. Changes in the sedimentology of shelf and offshore bioregions are attributed to decreasing energy levels and sediment transport mechanisms with distance offshore as described in section 3.

Differences between the texture of sediments in shelf bioregions are difficult to quantify as CWST and CWSP contain only nine and 13 samples, respectively. However, data from the NWST indicate that the sediments in this bioregion differ significantly in texture and composition from those in other shelf bioregions, with mud and gravel fractions regularly attaining >20% and bulk carbonate contents <20% locally. The NWST can be distinguished from all other bioregions by high mud content of sediments across the entire shelf. The NWST and CWSP are characterised by highly variable carbonate contents (standard deviation 22%). The NWSP is distinguished from the other bioregions by consistently high carbonate contents (>80%).


110°
120°
130°
10°
20°
Bioregions
Central Western Shelf Province
Central Western Shelf Transition
Central Western Transition
Northwest Province
Northwest Shelf Province
Northwest Shelf Transition
Northwest Transition
Timor Province
North West Marine Region boundary
EEZ boundary
Samples added for task
Samples with sediment data in MARS prior to task
DARWIN
Derby
Port Hedland
Carnarvon
Kalbarri
WESTERN AUSTRALIA
0
500 km
07-2243-54
WA
NT
QLD
SA
NSW
VIC
TAS

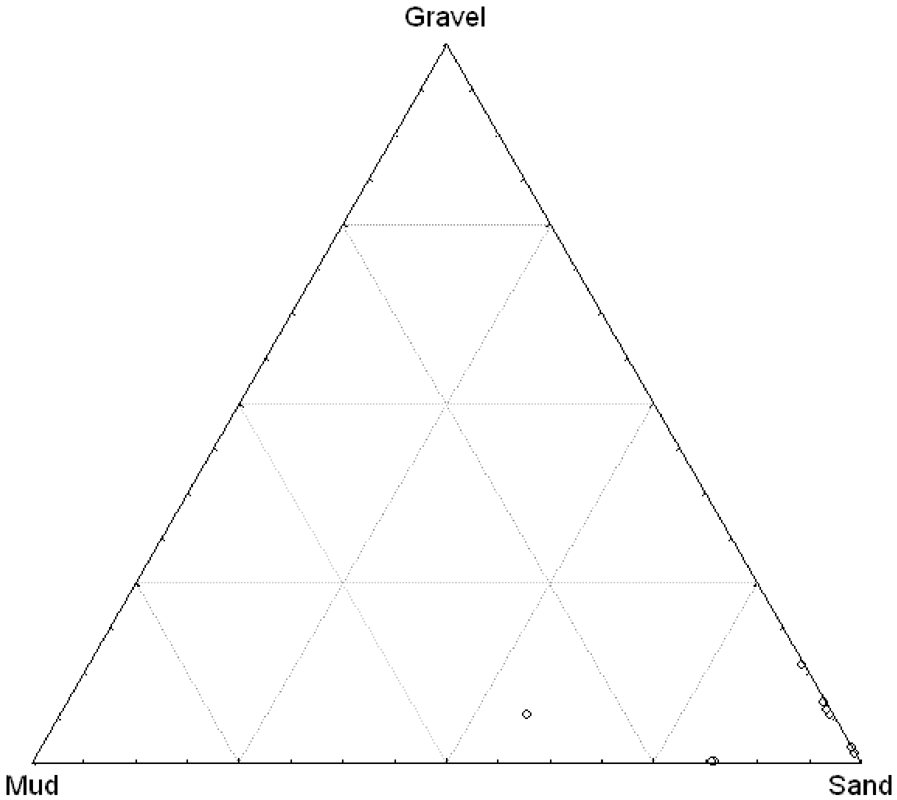
a)



b)

Figure 5.1. a) Sample coverage of bioregions within the NWMR; and b) sample density of each bioregion before and after the task.

a)



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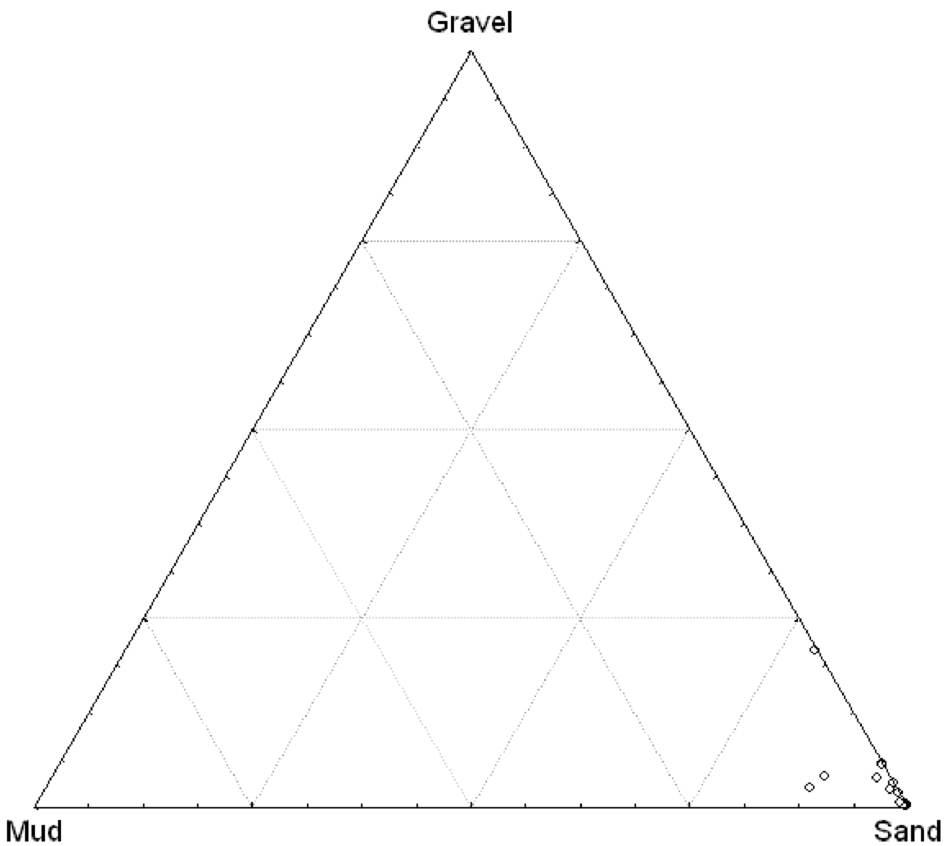

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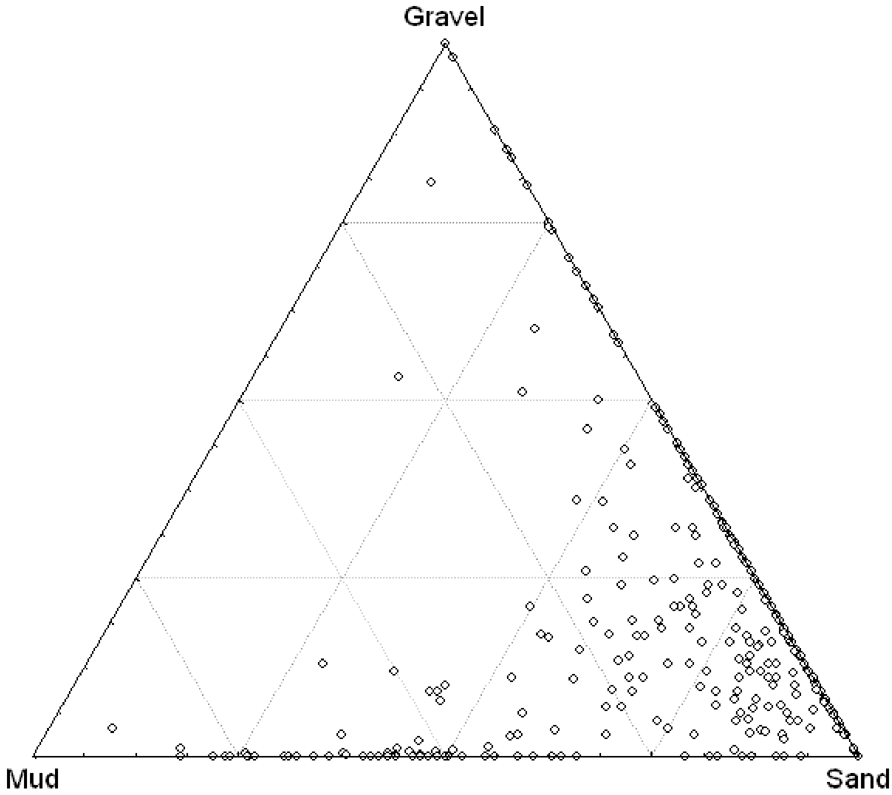

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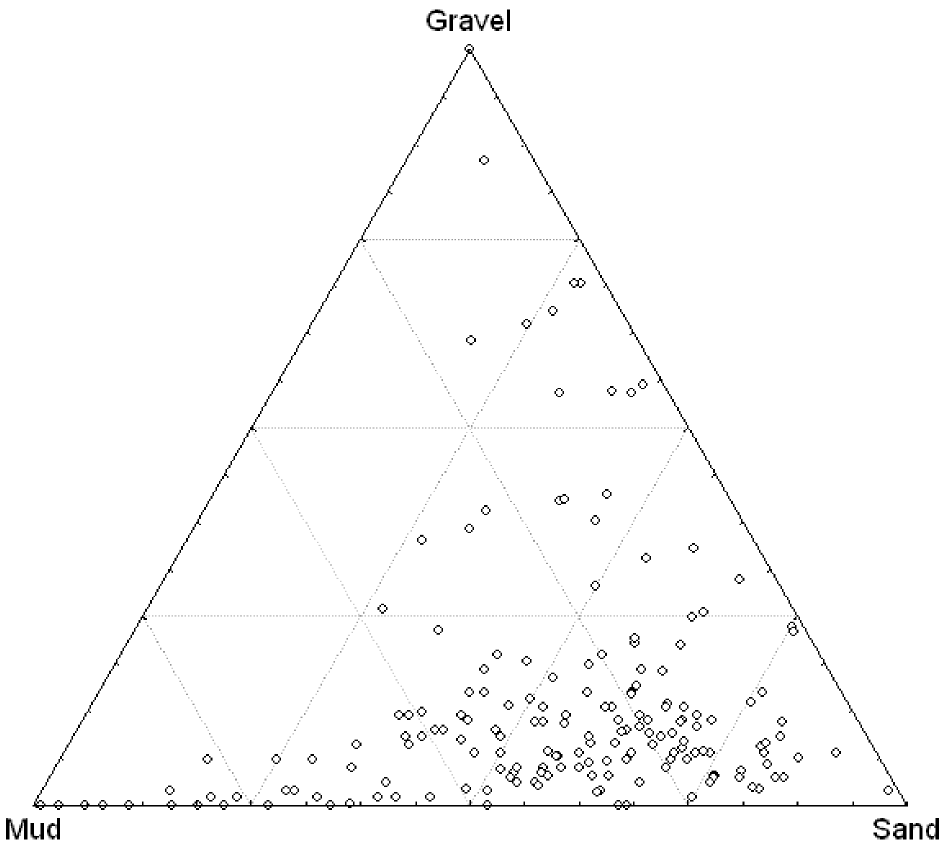


e)

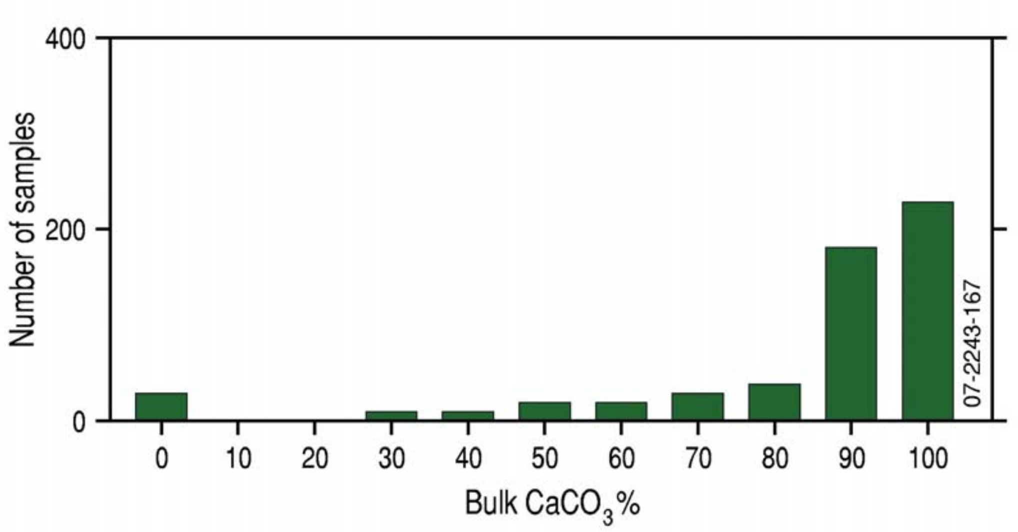
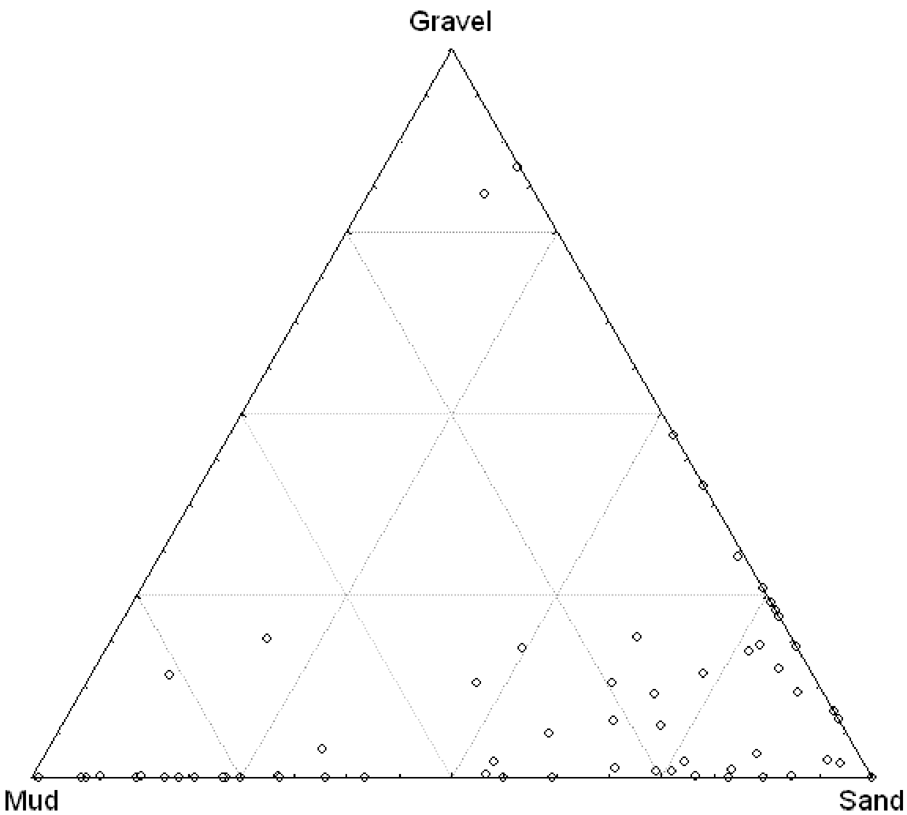
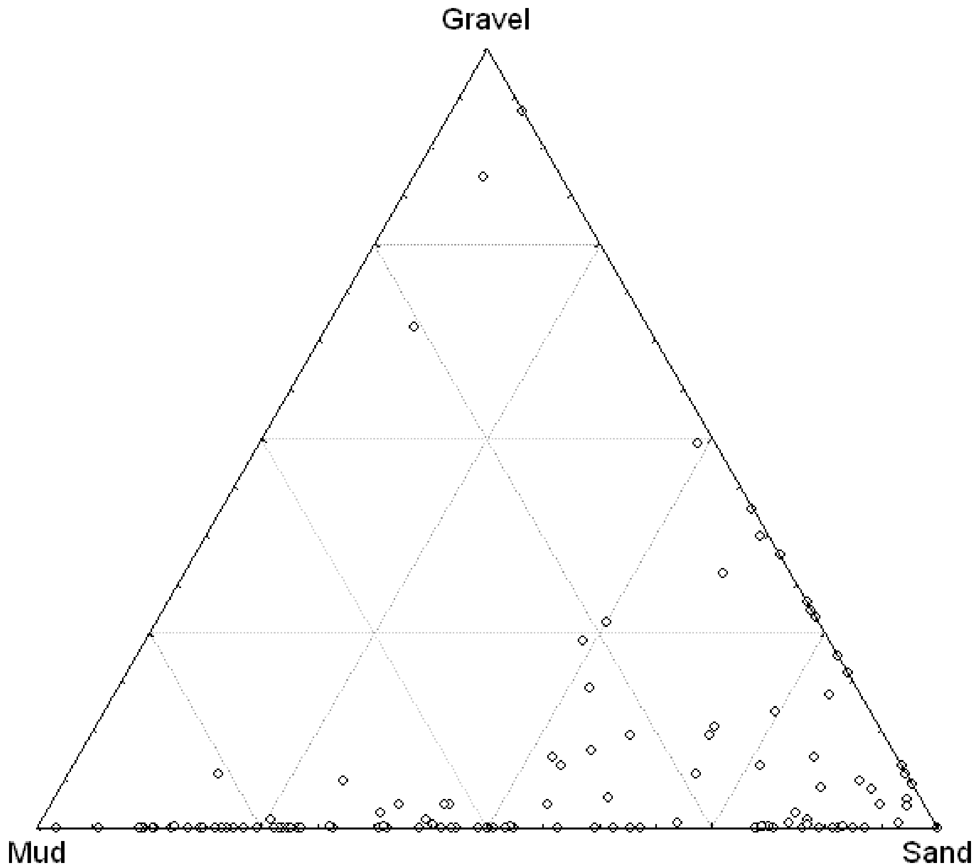


Figure 5.2. Textural composition (mud:sand:gravel ratio) of sediments in the shelf bioregions of the NWMR; a) Northwest Shelf Transition, b) Northwest Shelf Province, c) Central Western Shelf Transition, d) Central Western Shelf Province, and e) Carbonate content of all the above shelf bioregion sediments in the NWMR.

a)





b)

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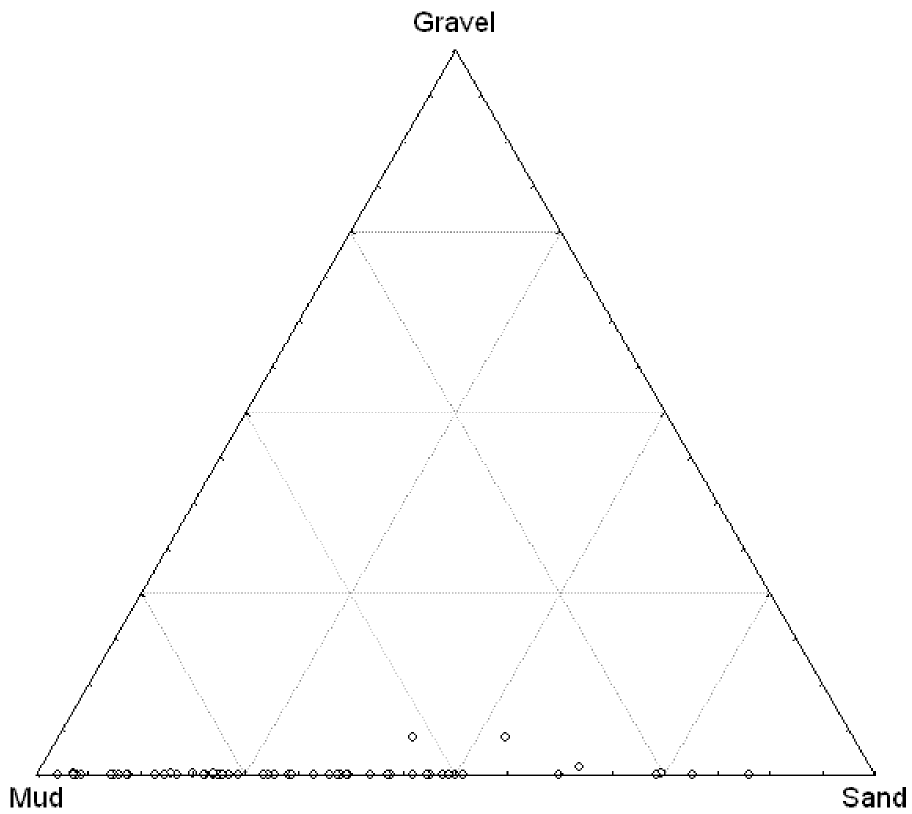

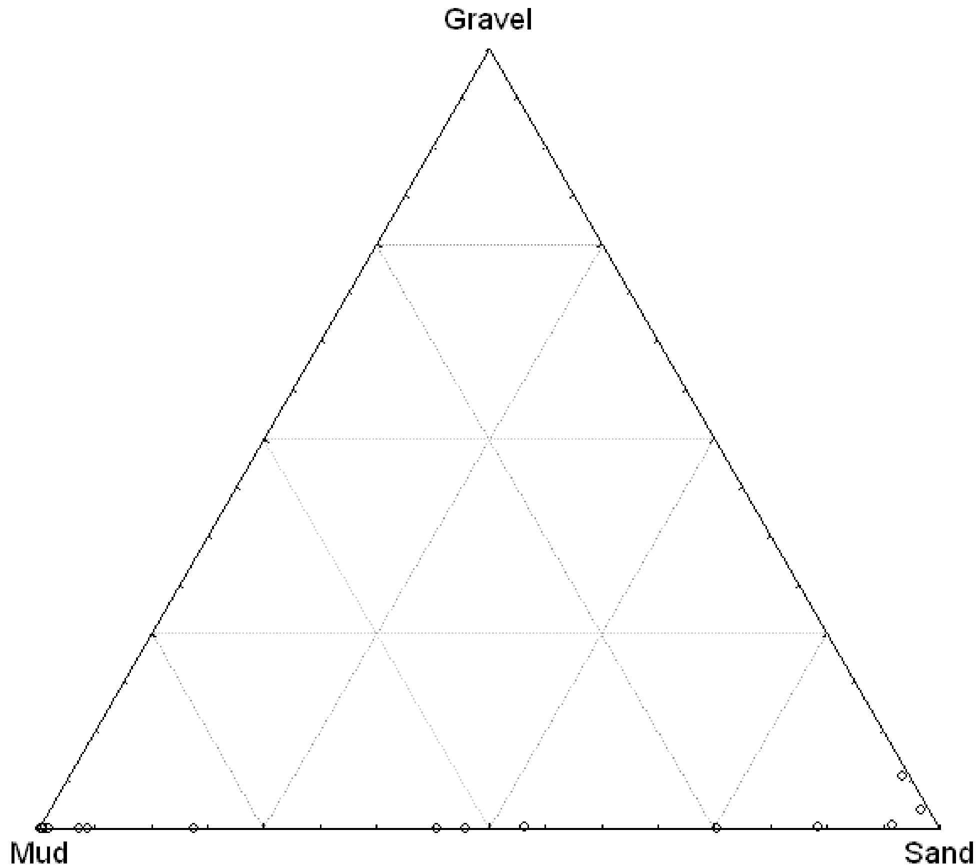

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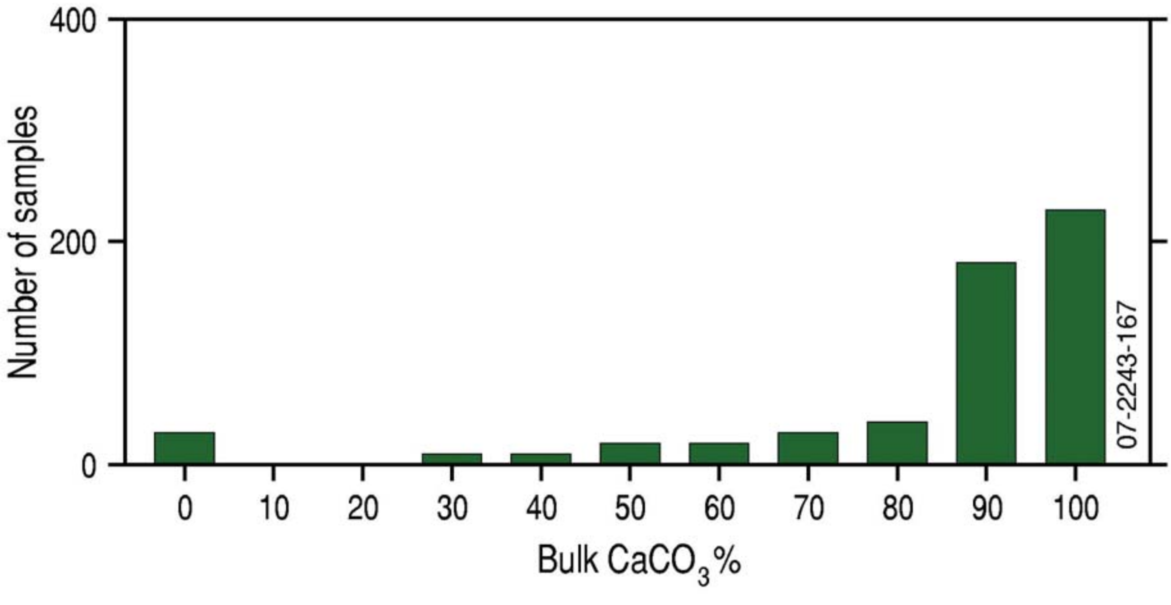


e)

Figure 5.3. a) Textural composition (mud:sand:gravel ratio) of sediments in the offshore bioregions of the NWMR; a) Central Western Transition, b) Timor Province, c) Northwest Transition, d) Northwest Province, and e) Carbonate content of all the above offshore bioregion sediments in the NWMR.

Table 5.1. Description of change in sample coverage of the NWMR area of bioregions with task

Bioregion	No. sample points (no. added for task)*	% NWMR Area	Average sample density (km²)
Northwest Shelf Transition	208 (62)	13	1:650
Northwest Shelf Province	463 (51)	20	1:450
Central Western Shelf Transition	9 (6)	<1	1:800
Central Western Shelf Province	13 (1)	3	1:2,550
Central Western Transition	15 (6)	15	1:10,850
Timor Province	77 (42)	15	1:2,000
Northwest Transition	125 (34)	17	1:1,450
Northwest Province	58 (33)	17	1:3,100

*The task that was set by the MOU between DEWHA and GA.

5.2. CENTRAL WESTERN SHELF TRANSITION (CWST)

5.2.1. Geomorphology and bathymetry

The Central Western Shelf Transition (CWST) covers a total area of 7,340 km², all of which occurs in the NWMR (Fig 5.1). This bioregion represents <1% of the total area of the NWMR (Table 5.1). The CWST is located on the continental shelf from north of Carnarvon to the tip of the North West Cape (Fig. 5.4a). It is bounded to the north by the Northwest Shelf Province and to south by the Central Western Shelf Province. The Central Western Transition and Northwest Province lie off the shelf adjacent to the CWST.

The CWST is located almost entirely on the seabed (unassigned). The shelf area included in the bioregion varies in width from approximately 25 km in the south to less than 1 km in places along the western edge of the Northwest Cape. Water depths vary from 0 to approximately 80 m near the shelf break in the south of the bioregion (Fig 5.5a). Approximately 460 km² (15%) occurs in water depths <10 m and has been excluded from this study. More than 55% of the remaining area of the bioregion (~15,000 km²) occurs in depths between 50 and 80 m (Fig 5.5b).

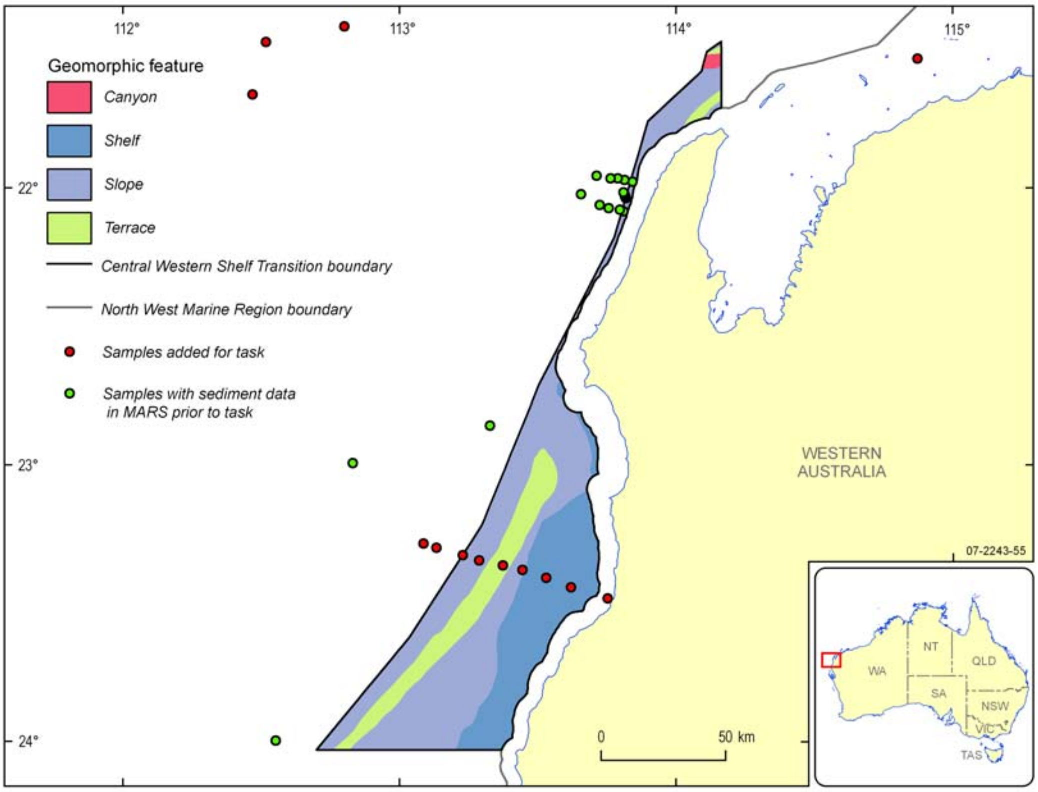
CWST is dominated by shelf (unassigned). Canyons and terraces are the only geomorphic features identified in this bioregion, and these cover ~1,140 km² (~15.55%) of the bioregion (Table 5.2). Canyons occur on the northern extent of the CWST, and terraces occur running in bands (~10 km in width) parallel to the shore.

Areas of unassigned shelf are both identified as significant features characterising the Central Western Shelf Transition. Due to the complex shape of the coast and current patterns in this region (Section 3.1.2), the sedimentology of the shelf in the CWST may differ from that of shelf areas elsewhere in the NWMR.

5.2.2. Sample Coverage

The CWST is represented by nine data points (Figs. 5.4a & 5.5a). Six of these occur in a cross-shelf transect south of the bioregion. The remaining samples occur in a line parallel to the shore towards the north of the bioregion. Samples provide coverage of the mid-range of water depths present on the shelf, occurring at depths between 50 and 250 m. Assays from these samples may not provide a good representation of the range of sediments occurring on the shelf due to small sample numbers. Despite targeted sample acquisition, only six samples were collected from reefs in the CWST; sedimentology of reefs is discussed in Chapters 3 and 6.

a)



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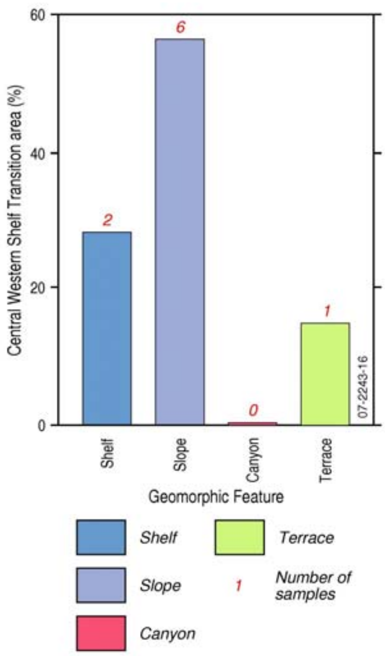
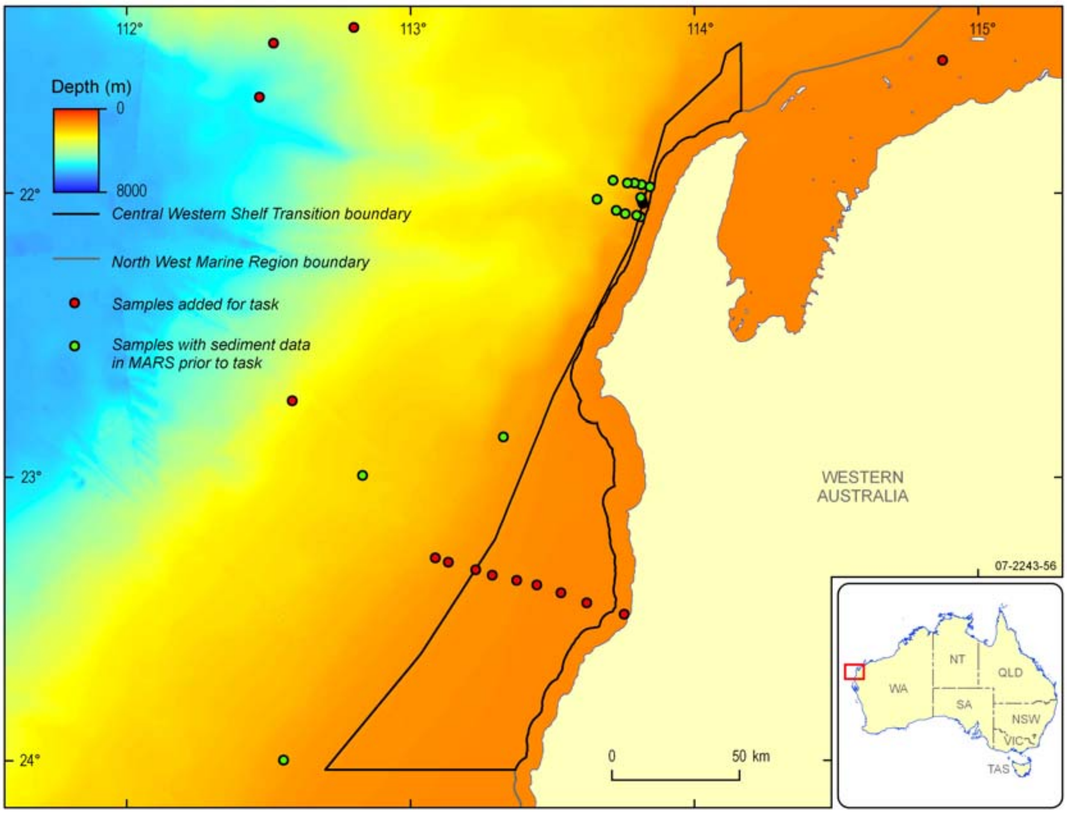


Figure 5.4. a) Geomorphology of the Central Western Shelf Transition (CWST) with location of samples; and b) Percentage area of each geomorphic feature within the CWST with number of corresponding sediment samples.



a)

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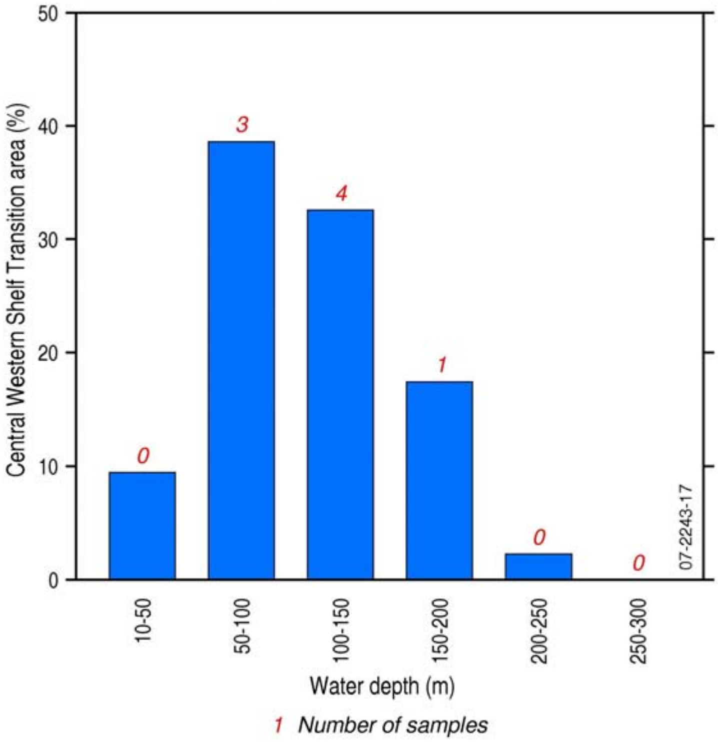


Figure 5.5. a) Bathymetry of the Central Western Shelf Transition (CWST) with location of samples; and b) Percentage area of bathymetry class within the CWST with number of corresponding sediment samples.

Table 5.2. Details of the geomorphology of the Central Western Shelf Transition.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Feature			
Unassigned shelf and slope	84.44	-	-
Canyon	0.50	0.34	0.03
Terrace	15.05	0.49	0.19

Table 5.3. Distribution of water depths covered by the geomorphology in the Central Western Shelf Transition.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Unassigned shelf and slope	35 - 210	105
Geomorphic Feature		
Canyon	180 - 210	195
Terrace	45 - 240	125

5.2.3. Sedimentology of the Central Western Shelf Transition

A total of nine samples were collected from the CWST, two from the shelf (unassigned), six from the slope (unassigned) and one from the terrace (Figs. 5.4a & 5.4b). Texture and composition of the sediments on the shelf are homogenous with the sand fraction comprising 98-99%, gravel <3%, and mud <1%. Bulk carbonate content and carbonate sand content attain 96%, and carbonate gravel attains 95%.

A total of six samples were obtained from the slope (unassigned). Assays indicate that this feature is characterised by relatively homogenous sediments dominated by sand, ranging between 82 and 93% with one sample containing 56% (Fig. 5.6). Mud is the next most abundant fraction with contents ranging between <1 and 18%, attaining 37% in one sample. Gravel attains up to 8% in all samples apart from one, which attains 14%. Bulk carbonate content ranges between 73 and 94% in all samples, carbonate sand ranges from 76 to 93%, and carbonate gravel ranges between 80 and 100% (Fig. 5.7). Carbonate mud attains up to 74% in three samples.

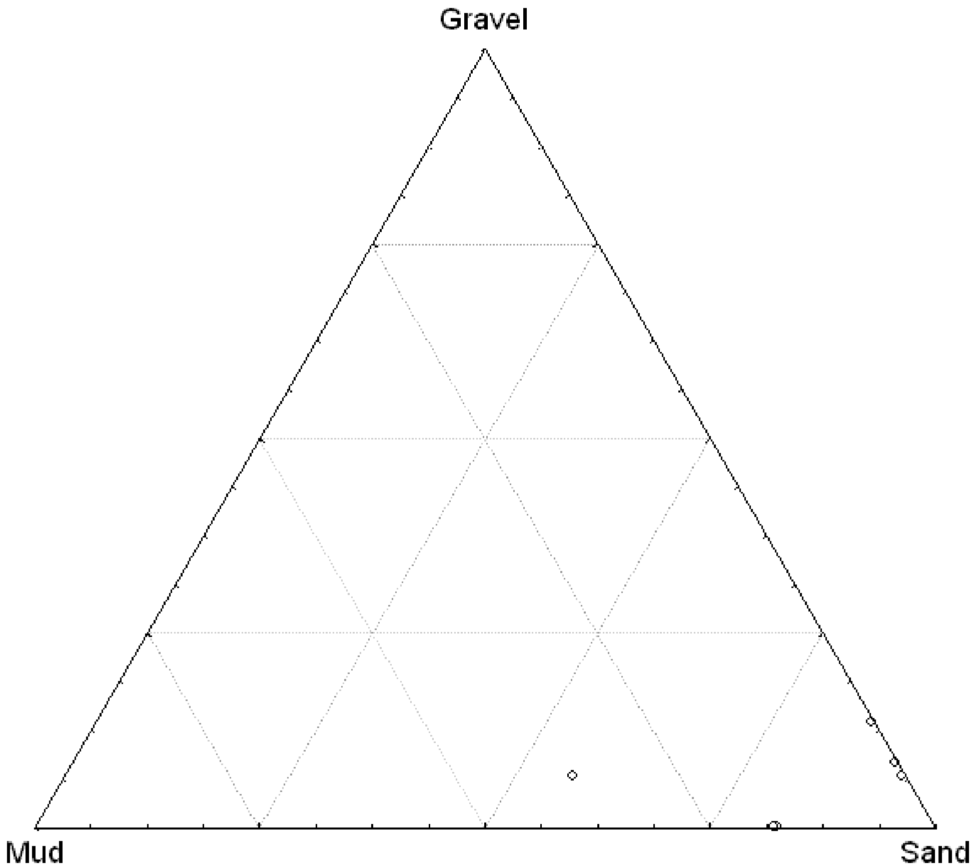


Figure 5.6. Textural composition (mud:sand:gravel ratio) of slope sediments within the CWST.

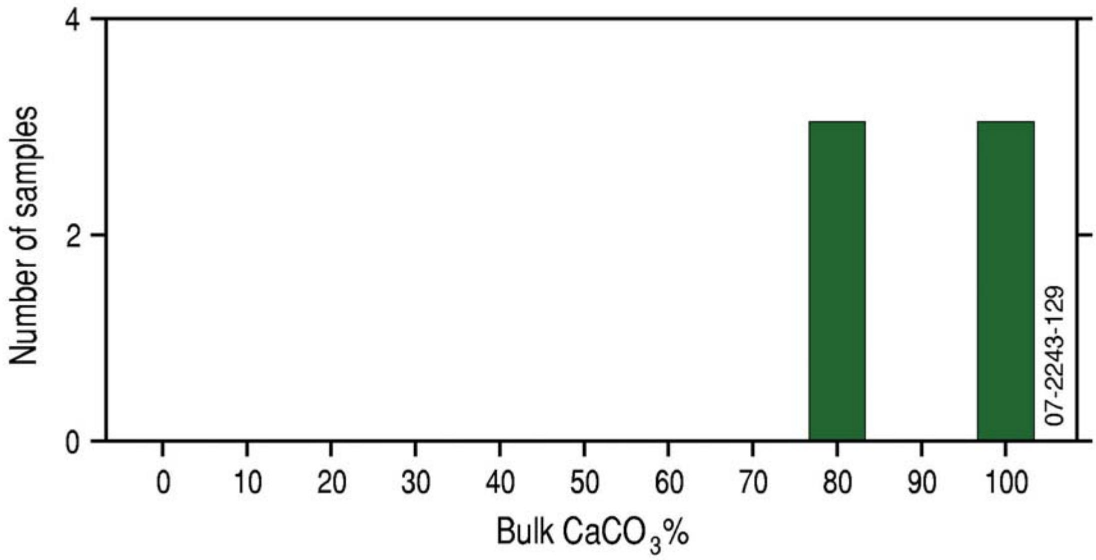


Figure 5.7. Carbonate content of slope sediments within the CWST.

5.3. CENTRAL WESTERN SHELF PROVINCE (CWSP)

5.3.1 Geomorphology and bathymetry

The Central Western Shelf Province (CWSP) covers a total area of 33,000 km², all of which is situated in the NWMR (Fig. 5.1). This bioregion represents 3% of the total area of the NWMR

(Table 5.1). The CWSP is located on the shelf offshore between Kalbarri and Coal Bay (Fig. 5.8a). The Bioregion lies on the southern boundary of the NWMR and is bounded to the north by the CWST and to south by the Southwest Shelf Transition (not included in the NWMR).

The CWSP is located on the shelf and upper slope (Table 5.4; Fig. 5.8a). The shelf varies in width from <20 km in the north to approximately 125 km in the vicinity of Shark Bay. Water depths range from 0 to approximately 100 m near the shelf break and in deeps/holes/valleys in the south of the bioregion (Fig 5.9a). Almost half of the area of the bioregion lies in depths between 50 and 100 m, and less than 2% lies in depths of >100 m. (Fig. 5.9b). Approximately 10,000 km^2 (>30%) occurs in water depths of <10 m and has been excluded from this study.

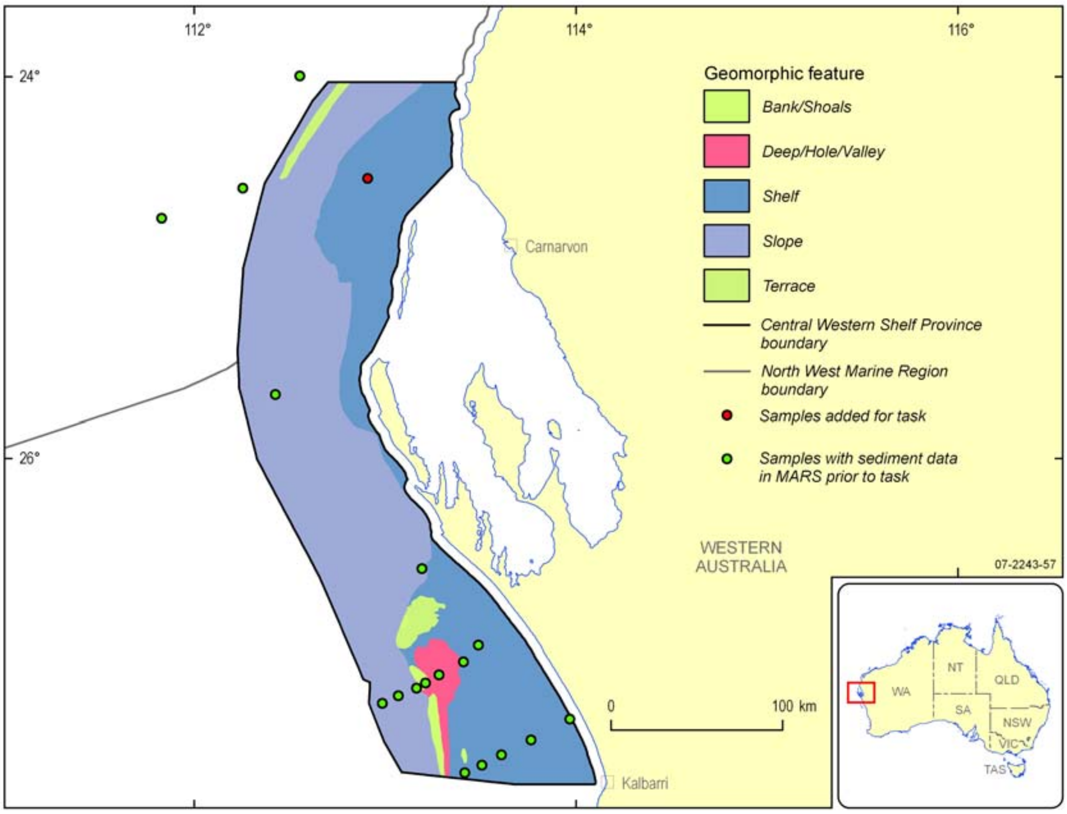
The CWSP is dominated by unassigned shelf and slope (30,000 km^2, 94% CWSP area). Small areas of deeps/holes/valleys (780 km^2, 2% CWSP area), terraces (710 km^2, 1%) and banks/shoals (330 km^2, 1%) are located within the shelf (Table 5.4).

Three significant geomorphic features are identified in the CWSP: Unassigned shelf and slope cover the majority of the bioregion. Banks/shoals in the CWSP form the second largest of three major occurrences of these features and lie at significantly lower latitudes than other banks/shoals in the NWMR.

5.3.2. Sample coverage

The CWSP is represented by 13 sample points (Fig. 5.8a). All but two of the total data points occur in two transects across the shelf and slope in the south of the bioregion in water depths ranging from 60 to >100 m. Data coverage is sparse to the north of Shark Bay with only one sample collected from this area.

Average sample density across the bioregion is approximately 1:2,550 km^2. Samples attain sufficient coverage to describe the sediment distribution on the shelf (unassigned) and slope (unassigned) only; other features contain <3 data points. Only two samples were collected from banks/shoals, and one sample was collected from deeps/holes/valleys. One sample was added to the shelf in the CWST during this study. No samples collected from tidal sand wave/sandbanks and banks/shoals were available for procurement. Sedimentology for these features is discussed in Chapter 3, 4 and 6. This sample distribution means that results for the shelf represent only the area offshore northwest of Kalbarri. The results best represent sediments occurring in shallow water, with approximately 50% of data points occurring in <40 m water depth (Fig 5.9a & 5.9b).



a)

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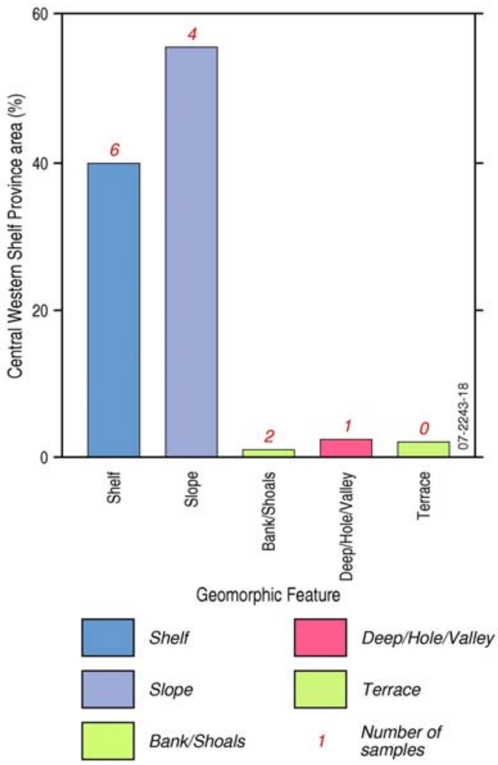
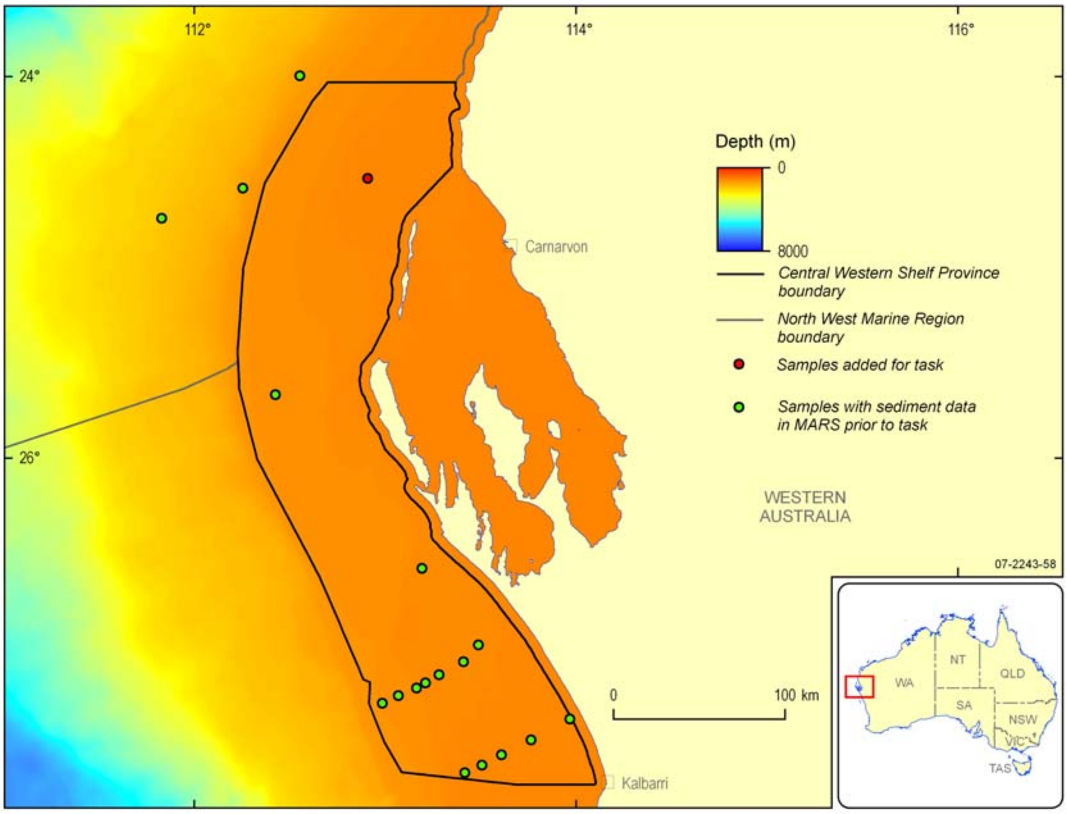


Figure 5.8. a) Geomorphology of the Central Western Shelf Province (CWSP) with location of sediment samples; and b) Percentage area of each geomorphic feature within the CWSP with number of corresponding sediment samples.



a)

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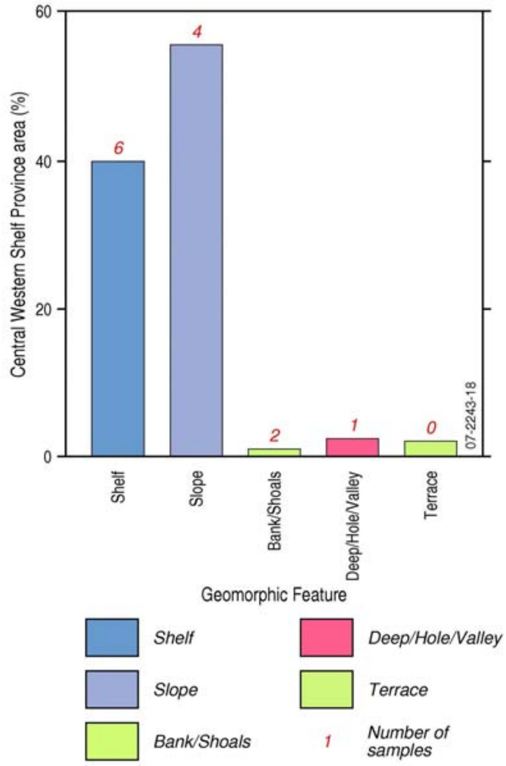


Figure 5.9. a) Bathymetry of the Central Western Shelf Province (CWSP) with location of sediment samples; and b) Percentage area of each bathymetry class within the CWSP with number of corresponding sediment samples.

Table 5.4. Details of the geomorphology of the Central Western Shelf Province.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Feature			
Unassigned shelf and slope	94.51	-	-
Bank/Shoals	0.99	1.12	0.65
Deep/Hole/Valley	2.37	0.84	0.47
Terrace	2.14	0.31	0.12

Table 5.5. Distribution of water depths covered by the geomorphology in the Central Western Shelf Province.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Unassigned shelf and slope	35 – 235	105
Geomorphic Feature		
Bank/Shoals	45 – 110	85
Deep/Hole/Valley	75 – 105	100
Terrace	50 – 175	120

5.3.3. Sedimentology of the Central Western Shelf Province

A total of 13 grain size and 15 carbonate assays are available for the CWSP in water depths of >10 m. All but one of these occurs on the shelf south of Shark Bay. Sediment texture in this area is relatively homogeneous. Sand is the dominant size fraction in all samples with contents ranging from 79 to 100% (Fig 5.10). Sand content exceeds 96% in seven out of 13 samples. Gravel comprises <5% in 10 out of 13 samples, and <1% in four samples. Mud comprises <1% in all but two samples, which attain up to 10%.

To the south of Shark Bay, carbonate content comprises >75%, and >89% to the north (Fig. 5.11). Carbonate content exceeds 80% in 14 samples (93%). Carbonate assays from the area of Shark Bay located at water depths <10 m show that similar variability is occurs across the embayment.

5.3.4. Sedimentology of Significant Geomorphic Features

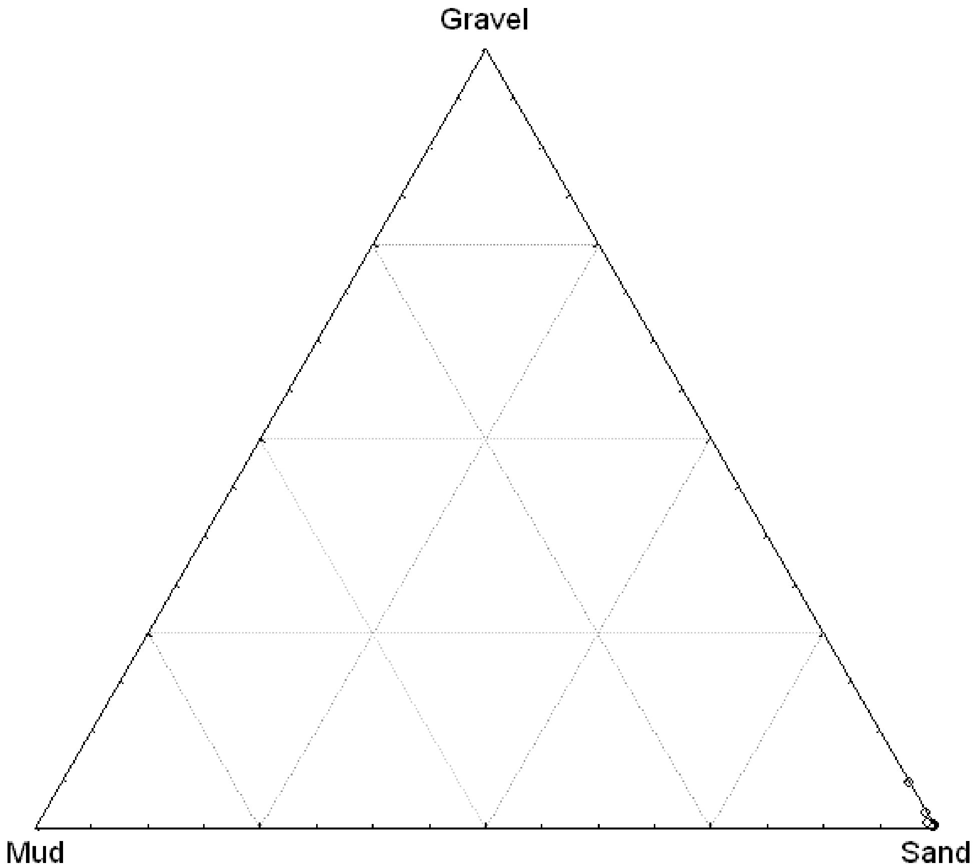
5.3.4.1. Dirk Hartog Shelf

A total of six samples were obtained from the Dirk Hartog Shelf. Assays indicate that this feature is characterised by relatively homogeneous sediments dominated by carbonate sands. Sand is the dominant fraction with contents generally ranging between 94 and 100% (Fig. 5.10a). Gravel is the next most abundant fraction with contents attaining <6%. Mud content attains

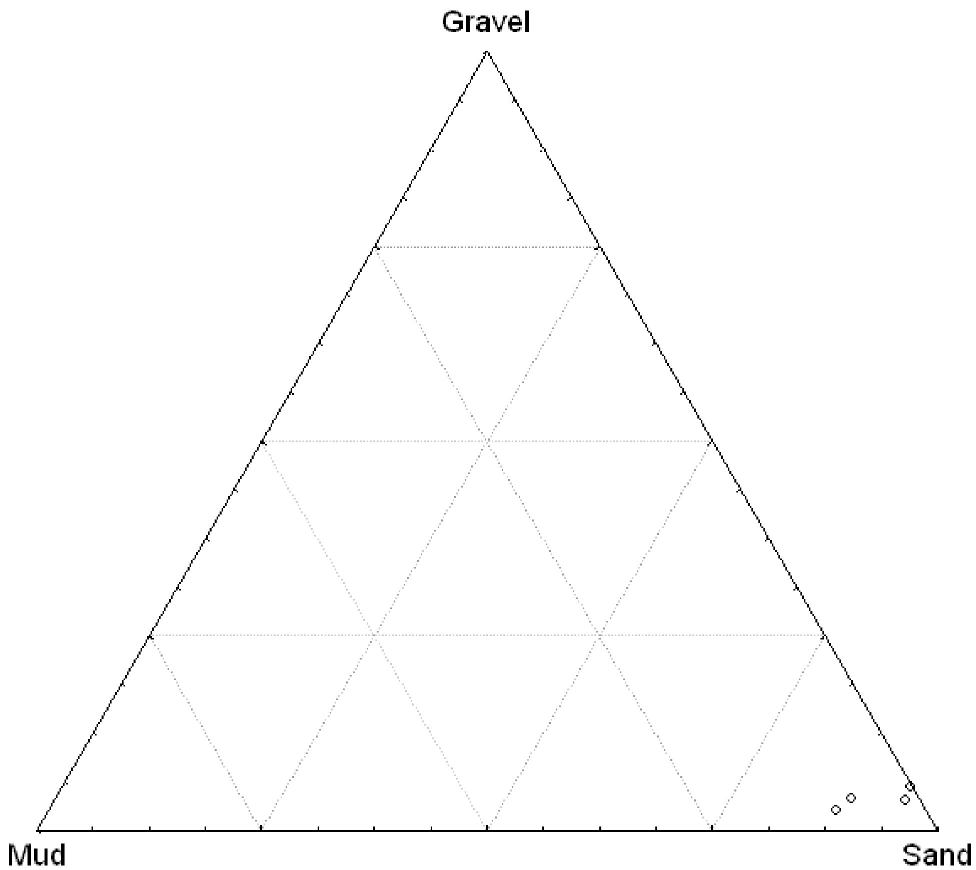
<1%. Bulk carbonate content ranges from 78 to 95% (Fig. 5.11a). Carbonate sand ranges between 93 and 95%, and carbonate gravel ranges from 75 to 100% in five samples.

5.3.4.2 Slope (unassigned)

A total of four samples were obtained from the slope (unassigned). Assays indicate that this feature is characterised by relatively homogenous sediments dominated by sand with contents ranging from 87 to 94% (Fig. 5.10b). Gravel is the next most dominant fraction with contents ranging between <1 and 6%. Mud content attains 7% in four samples. Bulk carbonate content ranges from 85 to 94%, carbonate sand ranges between 90 to 95% in four samples, and carbonate gravel ranges between 95 and 100% (Fig. 5.11b).



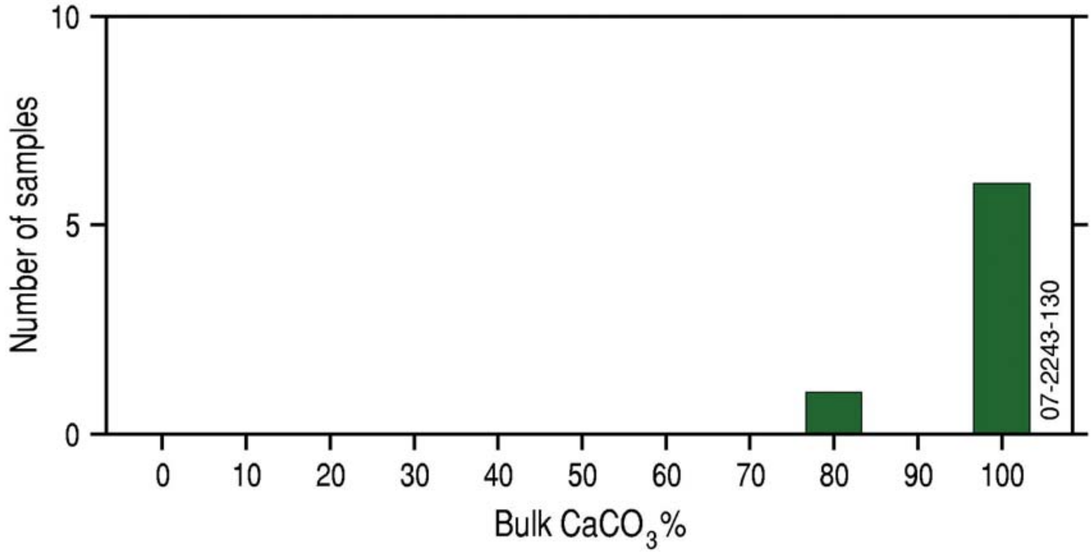
a)



b)

Figure 5.10. Textural composition (mud:sand:gravel ratio) of a) shelf and b) slope sediments within the CWSP.

a)



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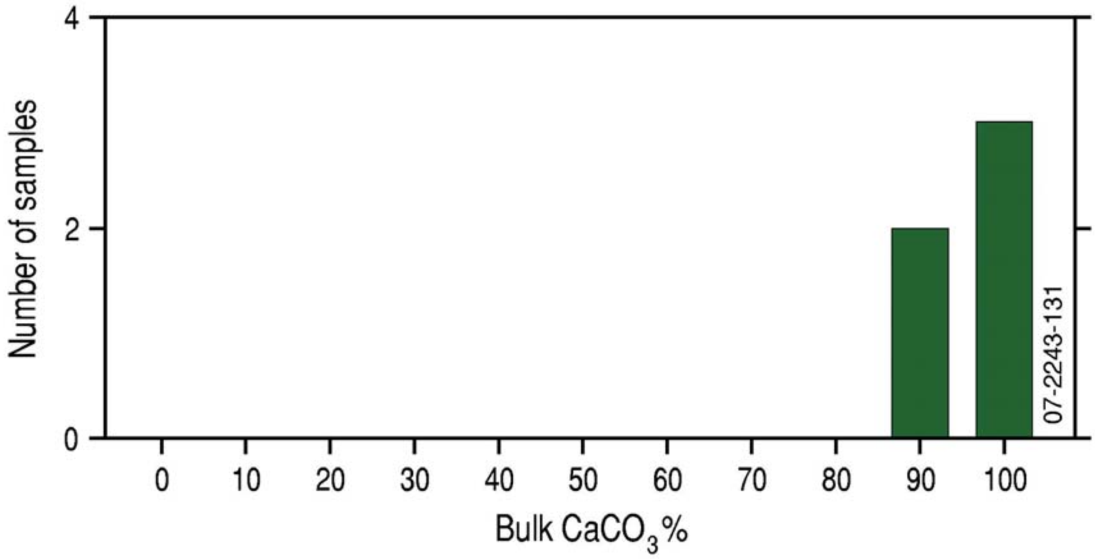


Figure 5.11. Carbonate content of sediments within the CWSP on a) shelf and b) slope.

5.4. NORTHWEST SHELF PROVINCE (NWSP)

5.4.1. Geomorphology and bathymetry

The Northwest Shelf Province (NWSP) covers a total area of 209,740 km^2, all of which is situated in the NWMR (Fig 5.1). This bioregion represents 20% of the total area of the NWMR (Table 5.1). The NWSP is located on the shelf between the North West Cape and Cape Bougainville. Between the southernmost point and Cape Leveque, the bioregion covers the entire width of the shelf. North of Cape Leveque, the bioregion extends from the shelf break to 80 km of the coast. In this area it is separated from the coast and bounded to the north by the Northwest Shelf Transition. The western boundary of the Northwest Shelf Province coincides with the Timor Province in the north and Northwest Transition and Northwest Province in the south.

The NWSP is located predominantly on the shelf and includes a section of the upper slope (Fig. 5.12a). The shelf is narrow in the south, approximately 50 km adjacent to Exmouth Gulf, and widens to >250 km north of Cape Leveque. Water depths vary from 0 to approximately 200 m along the shelf break and within the deeps/holes/valleys to the south of the bioregion. More than 45% of the bioregion lies in depths between 50 and 100 m (Fig. 5.13b).

Unassigned shelf and slope in the NWSP cover 122,990 km^2 (59% of the area of the NWSP). Terraces cover 45,570 km^2, (22% of the area of the NWSP) and deep/hole valleys 26,040 km^2, (12%). Plateaus cover 9,740 km^2, (5%), banks/shoals 2,310 km^2, (1%), and pinnacles 200 km^2, (0.1%) of the bioregions (Table 5.6).

Six significant geomorphic features are identified for the NWSP. The Rowley Shelf covers 47% of the bioregion and forms >70% of the area of the shelf in the NWMR. Banks/shoals in the NWSP display significant differences in morphology and dimensions from those in adjacent bioregions; they are therefore likely to be characterised by different sedimentology. Deeps/holes/valleys cover a significant area of the bioregion (26,040 km^2) and occur in two separate locations, each displaying morphology that distinguishes them from deeps/holes/valleys elsewhere in the NWMR. The Leveque Rise (a large plateau) is one of only two plateaus in the NWMR located on the shelf and extending into water depths as shallow as 100 m. Terraces located in water depths <200 m in the NWSP are unique to the northern NWMR; individual terraces cover larger areas and display morphology that differs from terraces occurring at these water depths in other shelf bioregions (Table 5.7). These form part of a suite of mid-shelf terraces that extend into the adjacent NWST and Timor Province Bioregions. However, the sedimentology in these features is best described in the NWSP as both the majority of the area of these features and best sample coverage occurs there.

Pinnacles occur in the south of the bioregion. These features cover a minor area of the NWSP (<1%) but form approximately 29% of the total area of this feature in the NWMR, with >70% of the pinnacles in the NWMR occurring outside of the NWST.

5.4.2. Sample Coverage

The Northwest Shelf Province is represented by 463 samples (Fig. 5.12a & b; Table 5.1). The majority of the samples occur on the mid-to outer-shelf, with more than 200 (>40%) samples located >60 km from the coast and 211 (46%) in water depths of >50 m. Average sample density across the bioregion is 1:450 km^2. Samples achieve sufficient coverage to describe the sedimentology in five of the six significant geomorphic features identified for this bioregion. A total of 178 samples were collected from the area of the Rowley Shelf; this gives an average density of 1:560 km^2 in this feature.

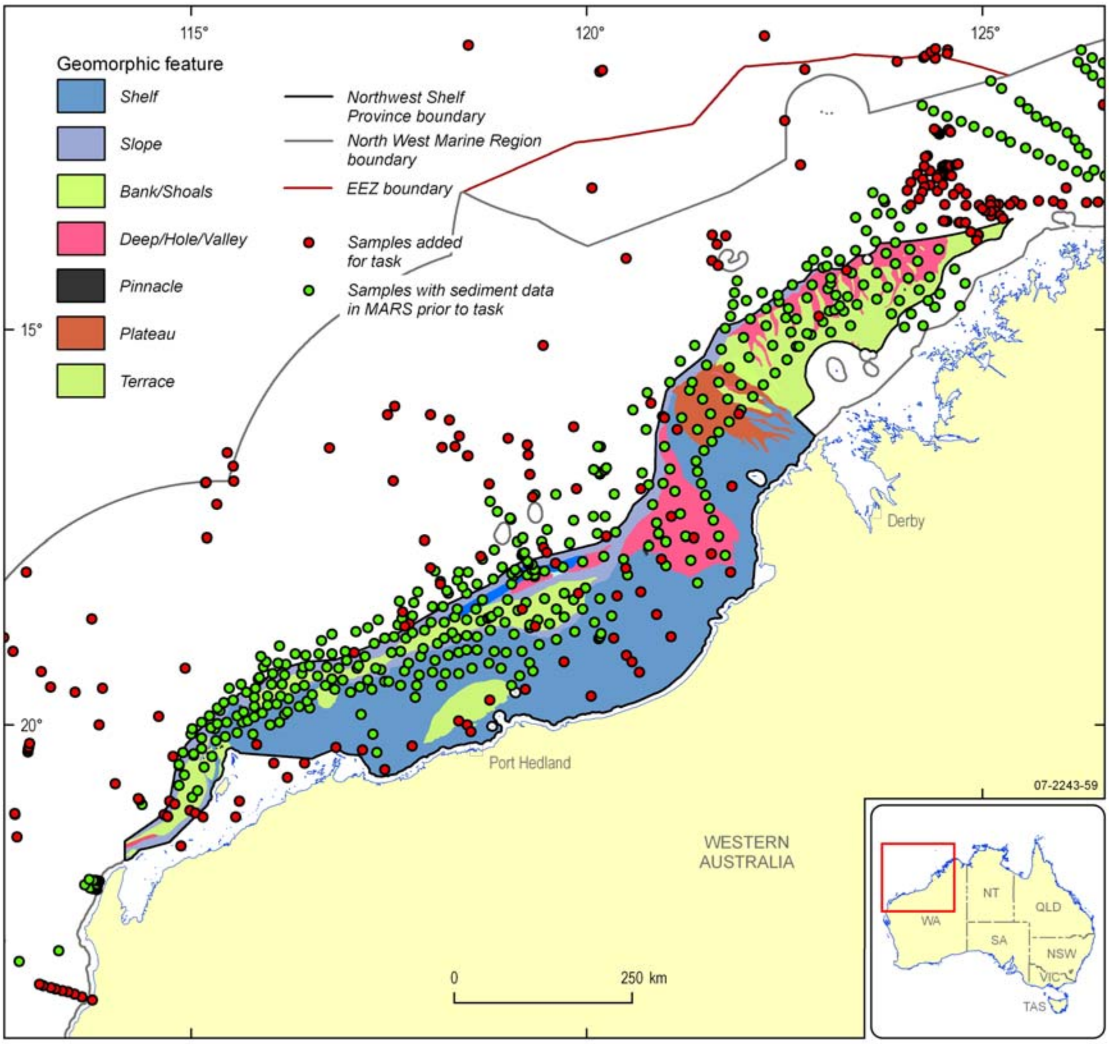
Terraces in shallow water (<200 m) in the NWSP contain 112 samples. Samples are mainly distributed across the area of a large terrace included in the north of the bioregion and a single smaller terrace on the inner shelf off Larrey Point. Samples are relatively evenly distributed within the area of these features, achieving an average density of 1:410 km^2.

The Leveque Rise contains 10 samples relatively evenly distributed across the feature, giving an average density of approximately 1:970 km^2. Deeps/holes/valleys contain 46 samples, relatively evenly distributed, with an average sample density of 1:570 km^2. Banks/shoals contain four samples, giving an average density of 1:800 km^2.

Only two samples were collected from pinnacles, neither of these occurs within the area of pinnacles identified as significant. No samples were available for tidal sand wave/sandbanks. Sedimentology for these features is discussed in Chapters 3, 4 and 6.

A total of 51 samples were added to the NWSP for this study; and, despite targeted sample addition, 23 of these were collected from shelf (unassigned). Samples from the current study increased coverage in deeps/holes/valley (4 samples added), plateau (1), ridge (1), slope (unassigned) (8) and terraces (13).

An uneven distribution of samples with higher densities on the outer shelf, particularly on the Rowley Shelf, means that assays are likely to be representative of the range of sediments occurring on the outer shelf but are unlikely to accurately represent the sedimentology of the inner-shelf. The few samples collected from banks/shoals means that the assays may not represent the range of sediments present in these features.


115°
120°
125°
15°
20°
Geomorphic feature
Shelf
Slope
Bank/Shoals
Deep/Hole/Valley
Pinnacle
Plateau
Terrace
Northwest Shelf
Province boundary
North West Marine Region
boundary
EEZ boundary
Samples added
for task
Samples with sediment data
in MARS prior to task
Derby
Port Hedland
WESTERN
AUSTRALIA
0
250 km
07-2243-59
NT
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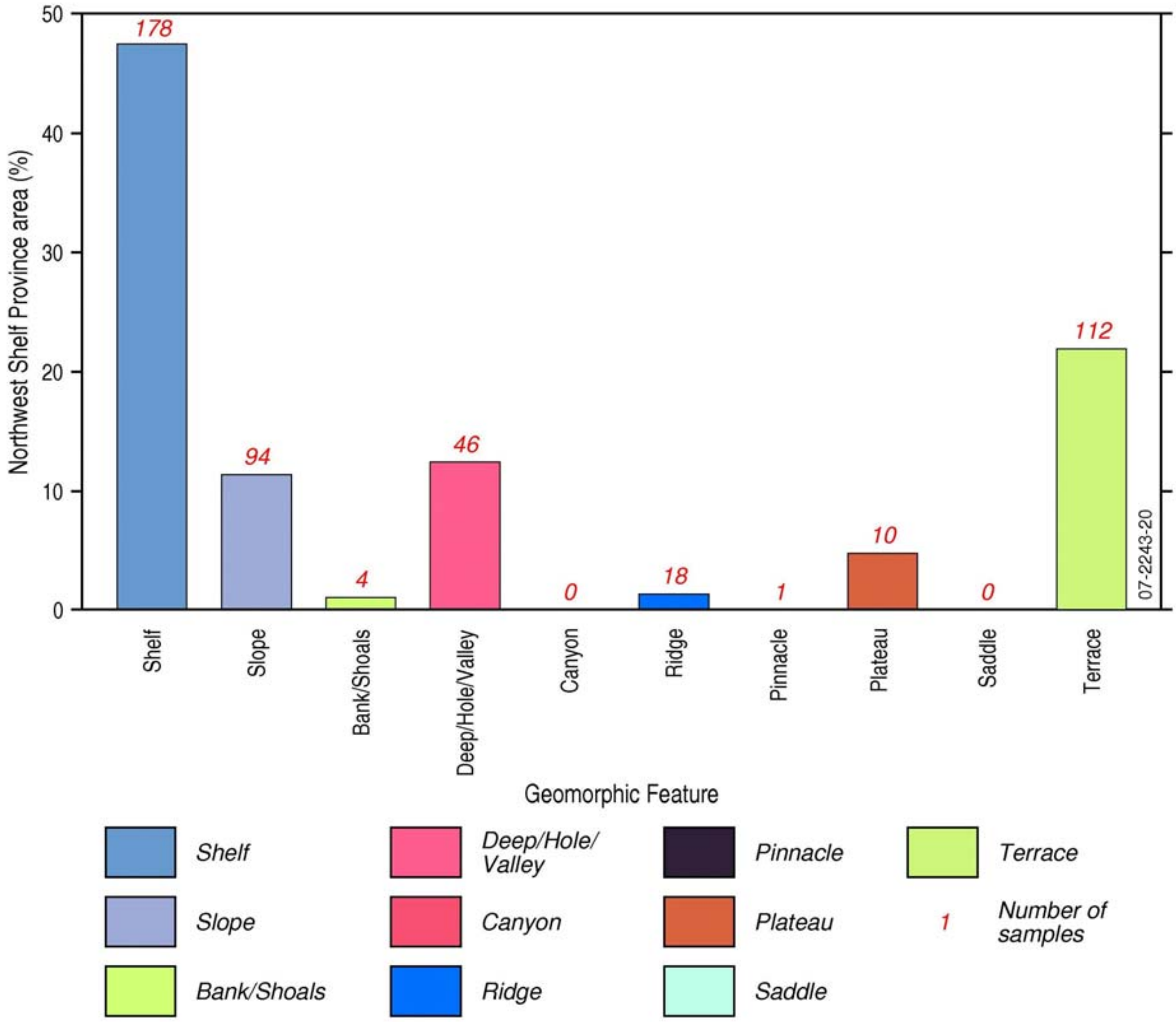
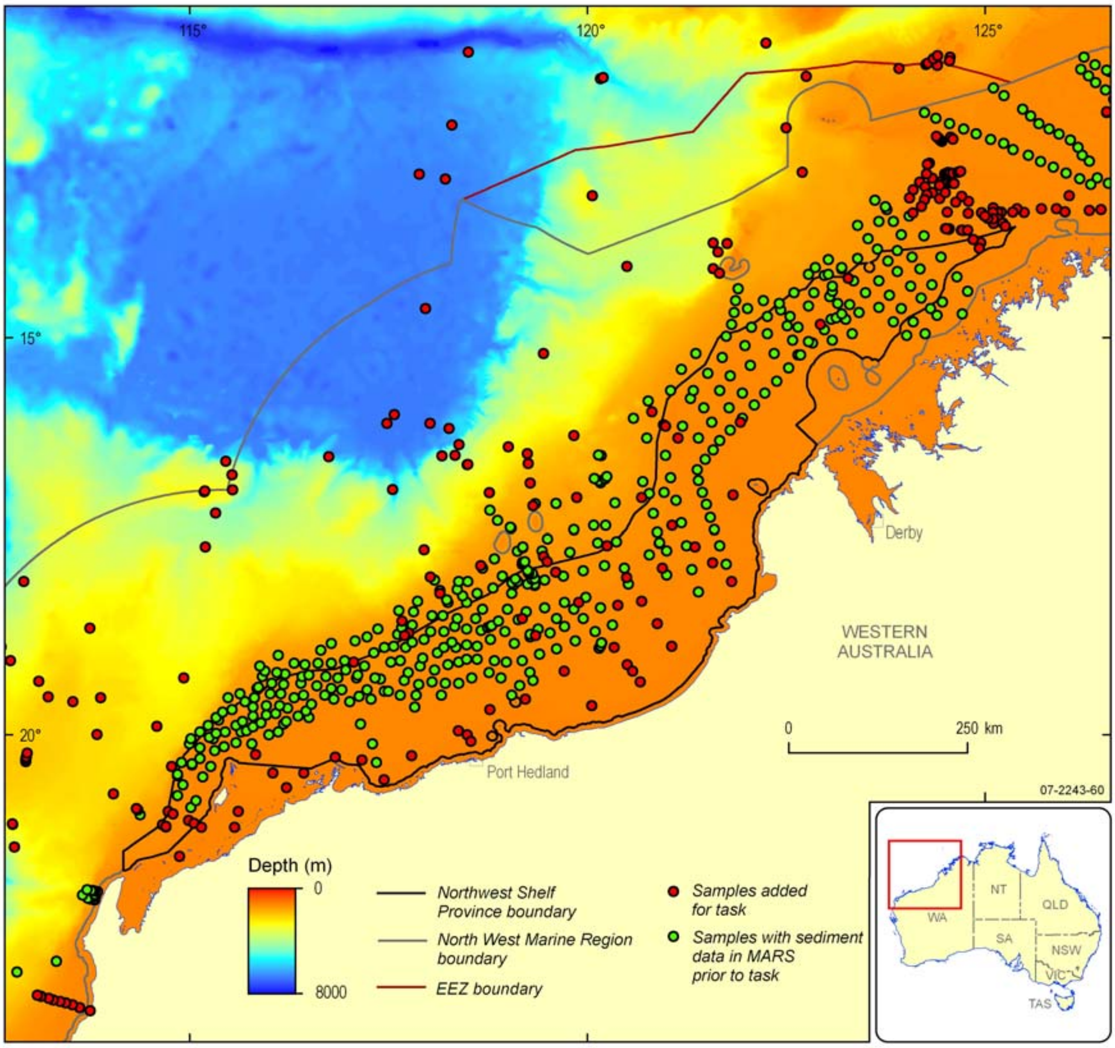
a)



b)

Figure 5.12. a) Geomorphology of the Northwest Shelf Province with location of sediment samples; and b) Percentage area of each geomorphic feature within the NWSP with number of corresponding sediment samples.

a)



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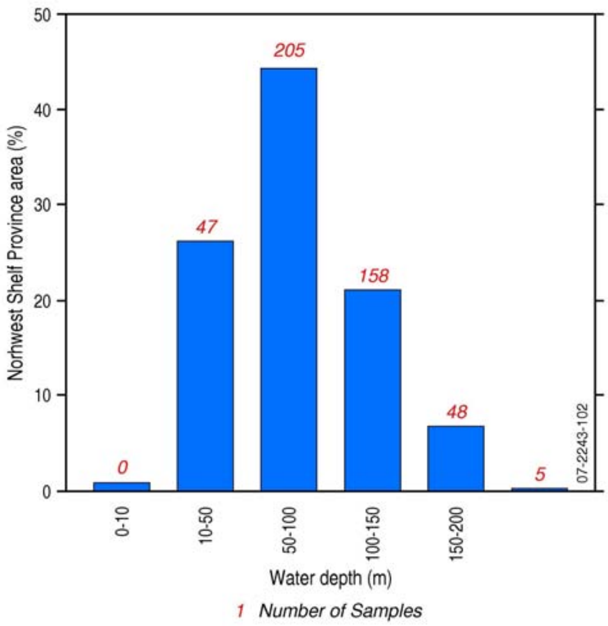


Figure 5.13. a) Bathymetry of the Northwest Shelf Province with location of sediment samples; and b) Percentage area of each bathymetry within the NWSP with number of corresponding sediment samples.

Table 5.6. Details of the geomorphology of the Northwest Shelf Province.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Feature			
Unassigned shelf and slope	58.64	-	-
Bank/Shoals	1.10	7.93	4.57
Deep/Hole/Valley	12.41	27.91	15.77
Canyon	0.10	2.03	0.21
Ridge	1.23	44.50	2.31
Pinnacle	0.09	29.20	3.87
Plateau	4.64	10.34	0.65
Saddle	0.05	2.85	0.61
Terrace	21.72	20.08	7.86

Table 5.7. Distribution of water depths covered by the geomorphology in the Northwest Shelf Province.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Unassigned shelf and slope	0 – 250	95
Geomorphic Feature		
Bank/Shoals	7 – 120	60
Deep/Hole/Valley	25 – 205	100
Canyon	130 – 190	165
Ridge	115 – 185	145
Pinnacle	5 – 160	60
Plateau	25 – 120	75
Saddle	150 – 165	160
Terrace	10 – 190	90

5.4.3. Sedimentology of the Northwest Shelf Province

A total of 463 grain size assays and 341 carbonate assays are available for the NWSP. Sediments in the south of the NWSP differ significantly from those in the north. South of Broome, sediment texture is relatively homogeneous and dominated by sand. Sand content exceeds 60% in most samples and exceeds 70% in 220 (66%) samples. Sand comprises <10% in three samples on the Leveque Rise and a small terrace west of Dampier. Gravel contents are <20% in 293 (88%) samples in this area and exceed 80% in only two samples that occur along the shelf break. Gravelly sediments may be present at other locations on the shelf but have not been detected due to low sample densities. Mud content exceeds 50% in 45 samples, <20% in 240 (>72%) and <1% in 146 (44%) samples. Mud is slightly more abundant in sediments within 100 km of the coast and within 100 km of the shelf break and is generally absent from sediments in the area between.

North of Broome, sediment texture is more variable. Sand and gravel dominate, with contents for both fractions ranging between 2 and 100%. The distributions of sand and gravel do not show any obvious spatial pattern. Mud content ranges from 0 to 78% in this area and exceeds 80% in three samples occurring on the slope adjacent to a deeps/holes/valleys feature, but it does not attain 1% in 73 (50%) samples.

Bulk carbonate content exceeds 80% in 312 (91%) samples in the NWSP. South of Broome carbonate contents of <60% are present locally but generally exceed 70%. North of Broome, carbonate content is <80% in 70% of samples, with local concentrations of 40%. Few carbonate assays are available for textural size fractions. However, those present indicate sand and gravel in the NWSP comprise >80% carbonate, and carbonate content of mud ranges from 82 to 86%.

5.4.4. Sedimentology of Significant Geomorphic Features

5.4.4.1. Unassigned slope/shelf area

A total of 272 samples were obtained from the shelf and slope. Sand is the dominant size fraction with contents ranging from 8 to 100%, with 237 of the 272 samples containing >50% sand (Fig. 5.14f). Gravel is the next most abundant fraction with contents generally ranging from <1 to 100%, and 12 samples >50%. Mud contents generally range from <1 to 88%, with 22 samples containing >50%. Areas adjacent to plateaus have consistently higher gravel content than other areas of the shelf and lower mud content. The mud content is low (<20%) adjacent to the reefs. However, these areas display large variations in gravel content, with samples locally comprising up to 75% sand or 90% gravel. Bulk carbonate content varies between 64 and 99% with 121 samples containing between 90 and 100% (Fig. 5.15f). Carbonate sand ranges between 69 and 97%, carbonate gravel ranges from 50 to 100% and carbonate mud ranges between 76 and 89%.

5.4.4.2. Banks/shoals

A total of four samples were obtained from banks/shoals (Fig. 5.14a). Sand is the dominant fraction with contents ranging between 22 and 76%; three of the four samples contain >50% sand. Gravel is the next most abundant fraction with contents attaining 20 to 26% in three of the four samples. Mud content is <20% in three of the four samples, although one sample located between deeps/holes/valleys contained 78% mud. Assays from banks/shoals in the NWIP suggest that these features may contain a high proportion of seabed sediments dominated by sand with minor gravel and little or no mud. Muddier environments may be present locally but are poorly represented or not sampled. Bulk carbonate content ranges from 60 to 93% (Fig. 5.15a).

5.4.4.3. Deep/hole/valleys

A total of 46 samples were obtained from deeps/holes/valleys. Sand is the dominant fraction of the sediments with contents generally ranging between 15 and 100% (Fig. 5.14b); 34 of the 46 samples contain >50% sand. Gravel is the next most abundant fraction with contents attaining

<1 to 85% and six samples containing >50%. Gravel content of sediments is variable, ranging from 3 to 80%. Mud content ranges between <1 and 62% but attains 74% in one sample where sand content is low. Bulk carbonate content varies between 66 and 99%, with 47 samples containing >65% carbonate (Fig. 5.15b). Carbonate sand content ranges between 85 and 96% in 11 samples, and carbonate mud ranges from 80 to 88% in four samples. Carbonate gravel ranges between 55 and 100% in 11 samples.

5.4.4.4. Leveque Rise (plateau)

A total of 10 samples were obtained from the Leveque Rise. Sediments characterising these features have large variations in the sand:gravel ratio and contain relatively little (<1%) mud (Fig. 5.14c). Sediments around the margins of this feature show similar attributes to those on the surrounding shelf and terraces. Bulk carbonate content ranges from 76 to 96% with 6 samples containing >90% (Fig. 5.15c).

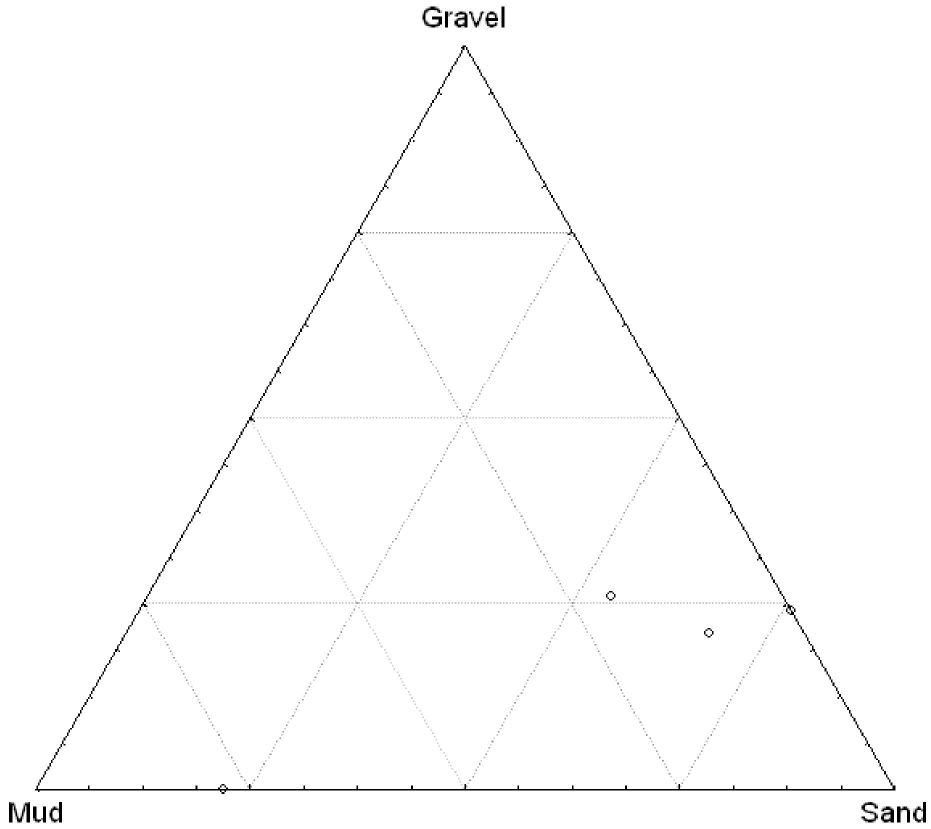
5.4.4.5. Shallow-water Terraces

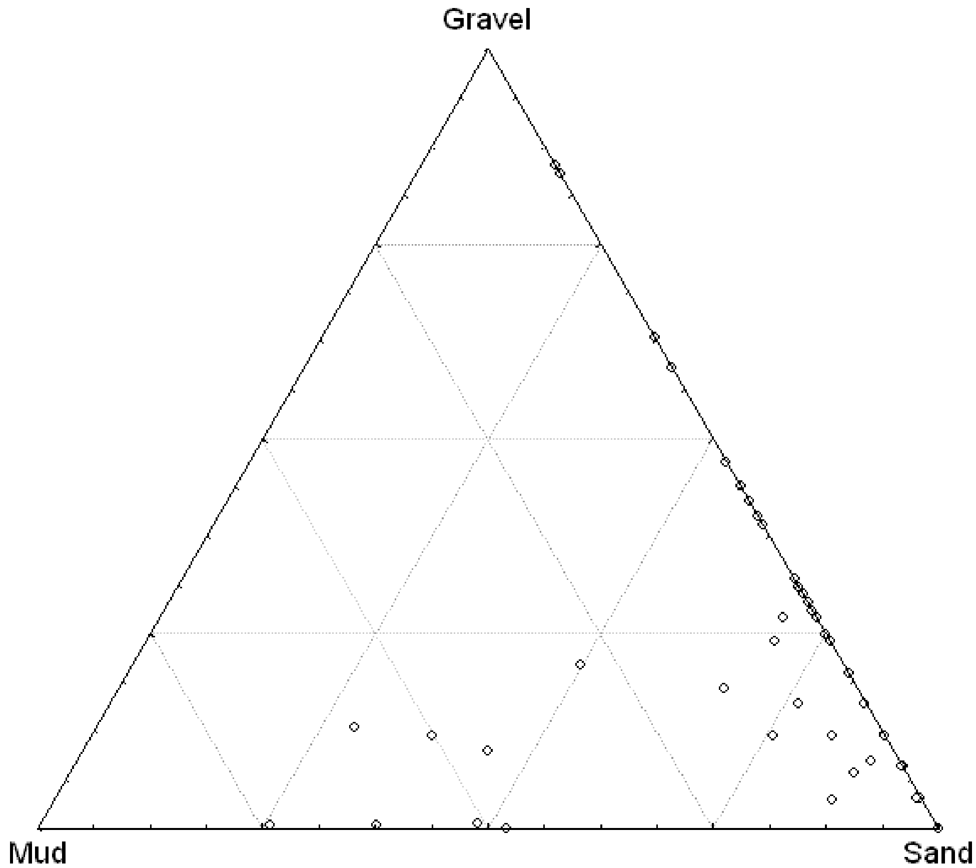
A total of 112 samples were obtained from terraces. Samples located adjacent to deeps/holes/valleys show highly variable sand:gravel ratios (Fig. 5.14e). Samples adjacent to areas of unassigned shelf showed less variable characteristics with sand dominating (30 - 55%) over gravel and mud (0-50%). Bulk carbonate content ranges from 63 to 100%, although one sample contains 42% carbonate. A total of 76 samples have bulk carbonate content >80% (Fig. 5.15e).

5.4.4.6. Ridges

A total of 18 samples were obtained from ridges. Mud is the most dominant sediment fraction with contents ranging between 9 and 77% and 11 samples containing >50% (Fig. 5.14d). Sand is the next most dominant fraction with contents ranging between 23 and 99% and five samples containing >50%. Gravel attains 20% on average and attains 36% in one sample. Bulk carbonate content ranges from 78 to 95% and attains >90% in six samples (Fig. 5.15d). Carbonate sand ranges between 93 and 98%, carbonate gravel ranges from 60 to 100% in seven samples and carbonate mud ranges between 88 and 89% in six samples.

a)





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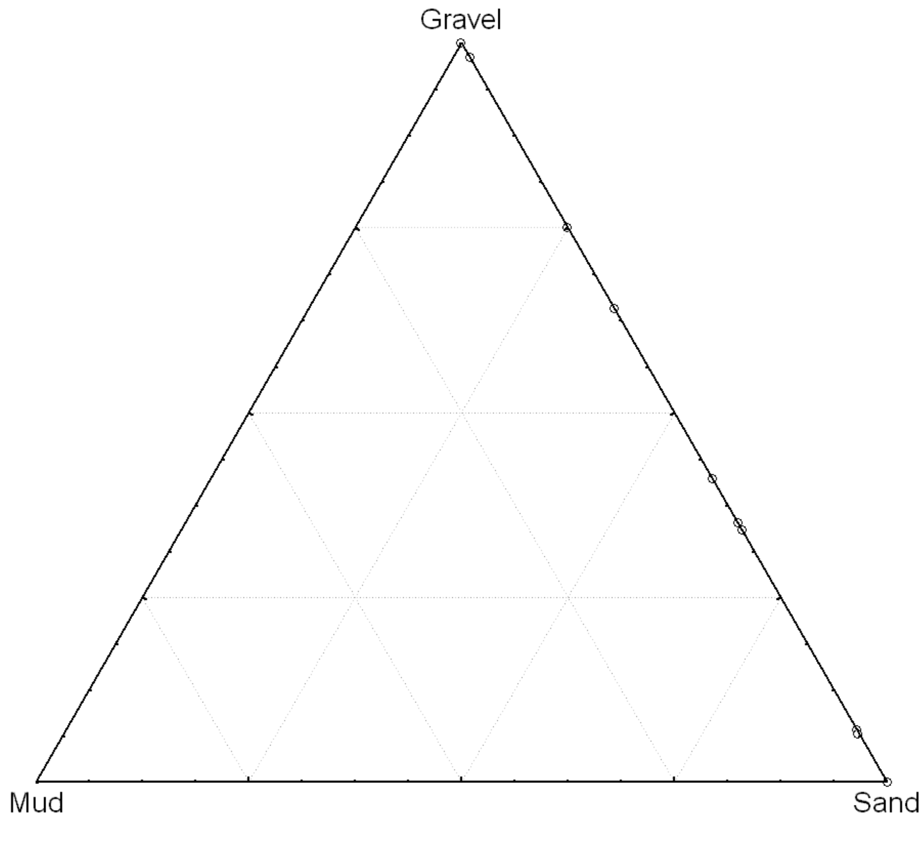
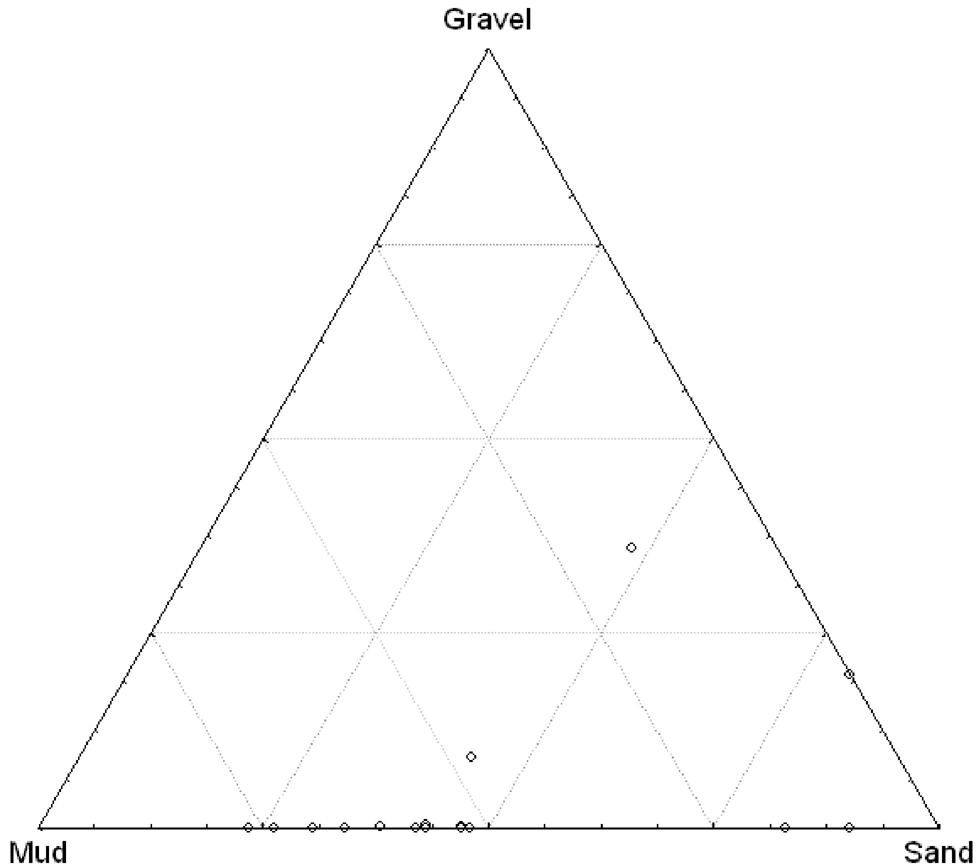
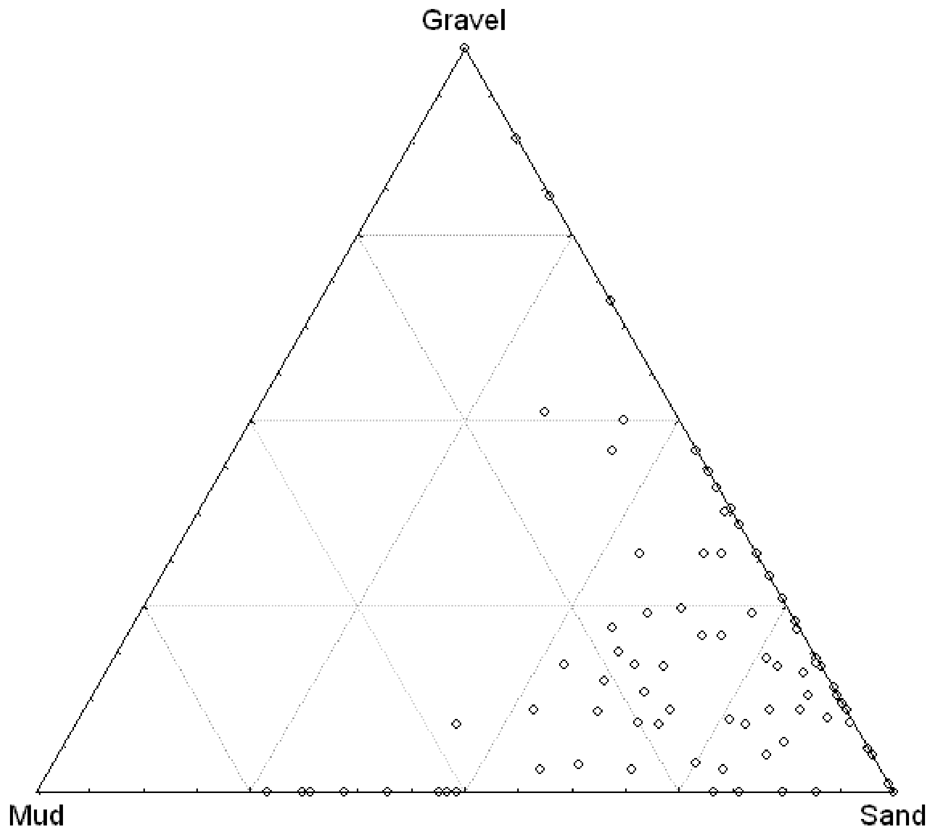
c)





d)

e)



f)

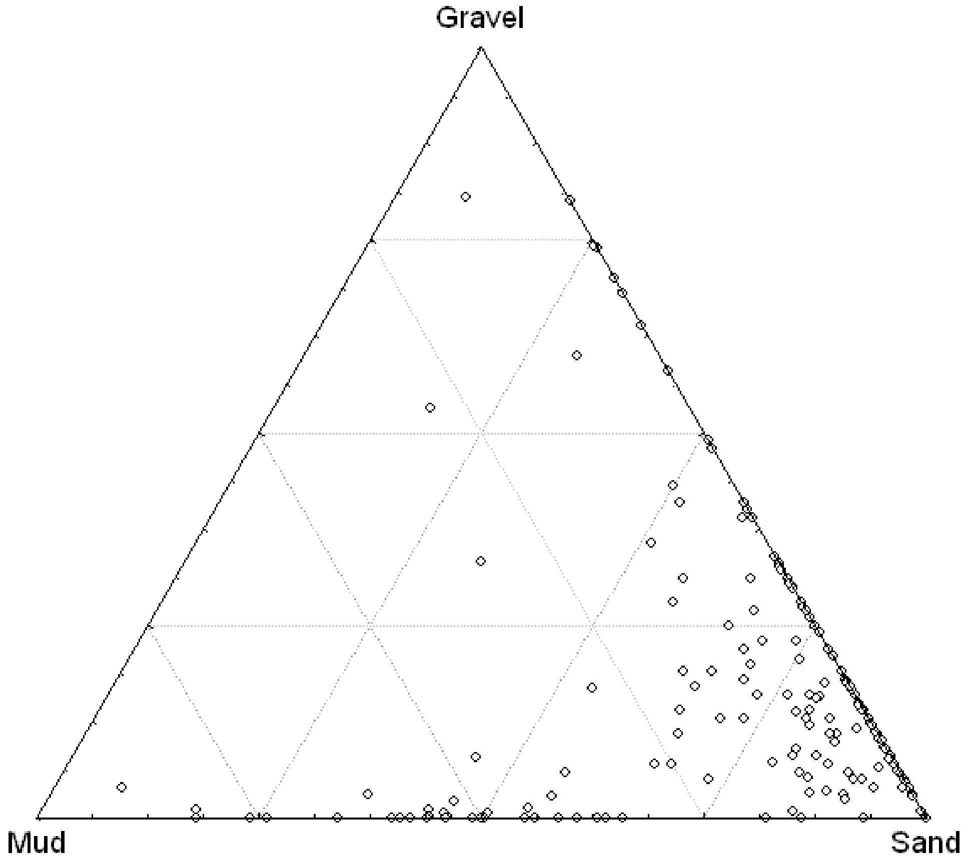
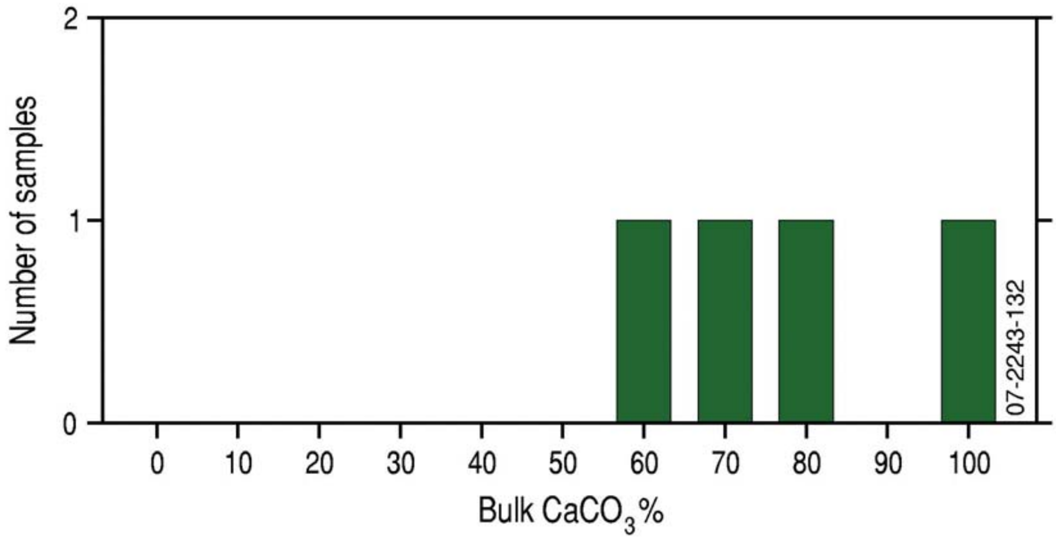
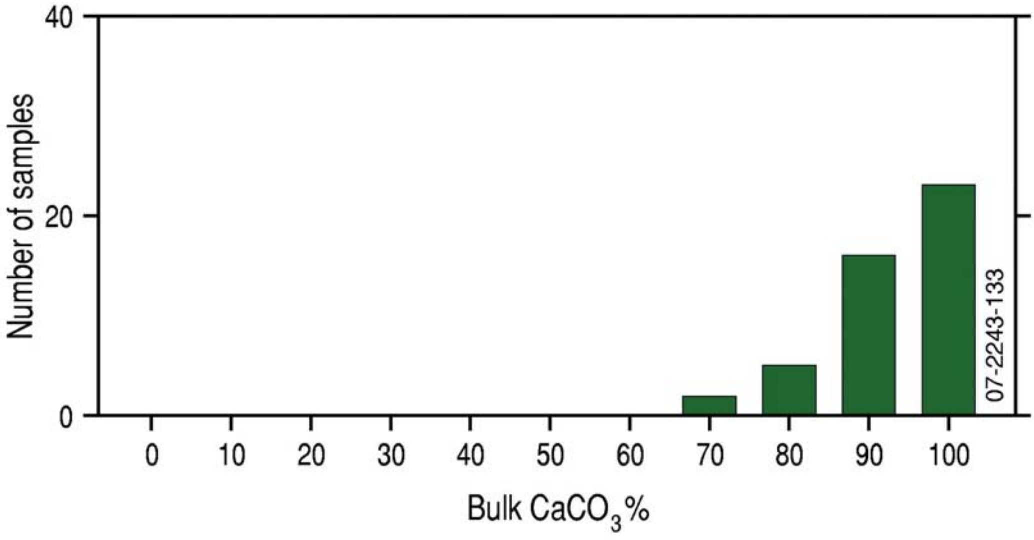


Figure 5.14. Textural composition (mud:sand:gravel ratio) of a) bank/shoal; b) deep/hole/valley; c) plateau; d) ridge; e) shallow water terrace; and f) shelf/slope sediments within the NWSP.

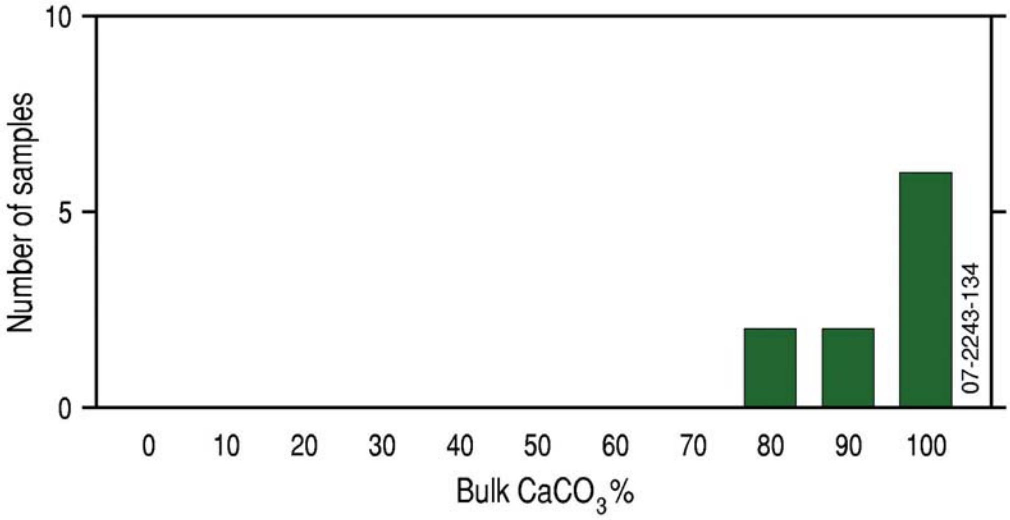
a)



b)


40
20
0
Number of samples
0
10
20
30
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-133

c)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Number of samples
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40
50
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70
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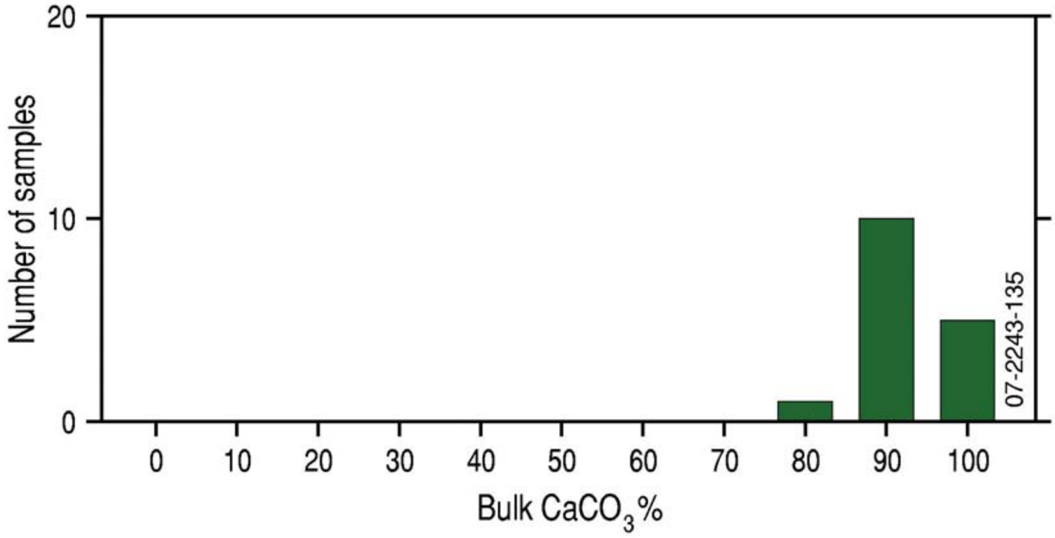
100
Bulk $CaCO_3$%
07-2243-134

d)


20
10
0
Number of samples
0
10
20
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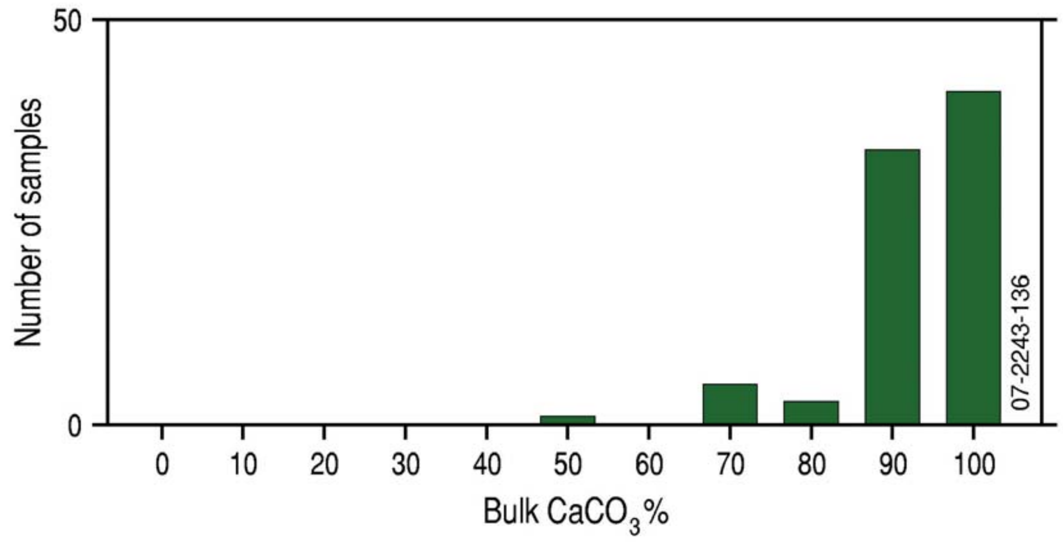
40
50
60
70
80
90
100
Bulk $CaCO_3$%
07-2243-135

e)



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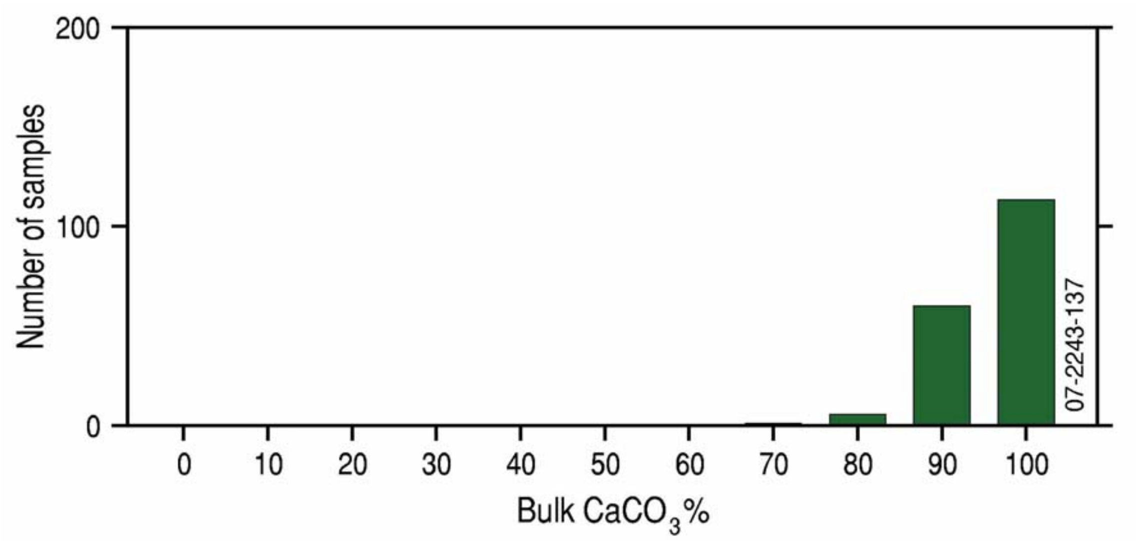


Figure 5.15. Carbonate content of a) bank/shoal; b) deep/hole/valley; c) plateau; d) ridge; e) shallow water terrace; and f) shelf/slope sediments within the NWSP.

5.5. NORTHWEST SHELF TRANSITION (NWST)

5.5.1. Geomorphology and bathymetry

The Northwest Shelf Transition (NWST) covers a total area of 308,450 km^2 of which 136,660 km^2 (56%) is situated in the NWMR and the remainder is found in in the North Marine Region (Fig 5.1). This bioregion represents 13% of the total area of the NWMR (Table 5.1).

The NWST extends from Cape Leveque to the eastern end of Melville Island. The NWMR boundary divides the bioregion through the centre of the Joseph Bonaparte Gulf (Fig. 5.1). The entire NWST is located on the shelf except for a single deeps/holes/valleys feature that extends onto the slope (this is an extension of the same feature that occurs in the NWSP) (Fig. 5.16a; Table 5.8). The offshore boundaries of NWST are complex. In the NWMR, it abuts the NWSP, Timor Province, and the unallocated area of the EEZ. The NWST extends > 300 km across the shelf from the inner boundary of the NWMR.

In the area of the NWST included in the NWMR, water depths vary from 0 to approximately 330 m (Fig. 5.17a; Table 5.9). This represents the full range of water depths that exist in the NWST. Within the NWMR, approximately 75% of the area of the NWST occurs at depths between 10 and 100 m. Less than 1% of the area occurs at depths of >150 m. The area of the NWST outside of the NWMR displays a similar bathymetric profile. Within the NWMR, approximately 14,000 km² (8%) occurs in water depths of <10 m and has been excluded from this study. This area lies mainly along the inner boundary of the NWMR, particularly in the Joseph Bonaparte Gulf (Fig. 5.16a).

The NWST comprises 10 geomorphic feature types, all of which are represented in the area located in the NWMR. Shelf (unassigned) forms 15% (19,940 km²) of the area of the NWST within the NWMR but dominates area of the NWST outside of the NWMR. The remaining area within NWMR is composed of terraces (42,510 km², 31% bioregion area in NWMR) followed by banks/shoals (26,430 km², 19%), basins (19,740 km, 14%), plateaus (14,030 km², 10%), deeps/holes/valleys (8,150 km², 6%) and sills (3,720 km², 3%). Tidal sand-wave/sandbanks and reefs total <1,720 km² (<2%) and occur locally. Pinnacles are abundant in the NWST although they cover <1% of the bioregion area (Fig. 5.16b; Table 5.8).

A total of eight significant features occur in the NWST. The large number of significant features selected for this bioregion reflects the relative complexity of the seabed and observations that sedimentology of this region differs from elsewhere in the NWMR. Features are likely to contain seabed environments not found elsewhere in the NWMR.

On the Sahul Shelf, large terraces occur in water depths of <300 m (Table 5.9), and deeps/holes/valleys cover significant areas and distinguish the seabed for this bioregion from that occurring in adjacent bioregions. Banks/shoals in the NWST form more than 90% of the total area of this feature in the NWMR. Basins in the NWST, including the Bonaparte Depression, are the only basins in the NWMR. They contain higher mud and gravel contents than sediments found elsewhere on the shelf in the NWMR (Chapter 4). Deeps/holes/valleys in the NWST, and particularly within the Bonaparte Depression, contain sediments differing from sediments found in these features elsewhere in the NWMR. The Londonderry Rise, a large elongate plateau, is considered significant as it covers a large area of the NWST. Its narrow morphology, bathymetric range (10 to 190 m) and spatial relationship to a range of other features make it unique within the NWMR. Tidal sand wave/sandbanks in the NWST form 100% of the area of these features occurring in the NWMR and >5% of the area of these features in the EEZ, and they are likely to contain sediments differing from sediments found in these features elsewhere in the EEZ. The area of tidal sand wave/sandbanks analysed for this study form approximately 50% of a larger occurrence of these features in the south of the Bonaparte Gulf; the remaining area of these features occurs in water depths <10 m. Pinnacles are abundant, particularly in the north east of the bioregion. These comprise 61% of the area of pinnacles in the NWMR and 8% of the area of this feature in the EEZ.

5.5.2. Sample Coverage

The area of the NWST located in the NWMR is represented by 208 samples. These occur mainly in NW – SE transects extending from the coast inside the Joseph Bonaparte Depression to the EEZ boundary and in clusters on the mid-shelf near the eastern boundary of the bioregion. Few samples occur on the inner shelf south of Cape Londonderry (Figs. 5.16a).

Average sample density across the assessed area of the bioregion is approximately 1:650 km^2. Samples achieve sufficient coverage to describe the sediment distribution in all six of the significant geomorphic features identified for this bioregion. A total of 42 samples were collected from the Sahul Shelf; this gives an average density of approximately 1:470 km^2. However, the uneven distribution of samples means that results are likely to only represent sediments present in the Joseph Bonaparte Depression and likely give no indication of sediments occurring south of Cape Londonderry.

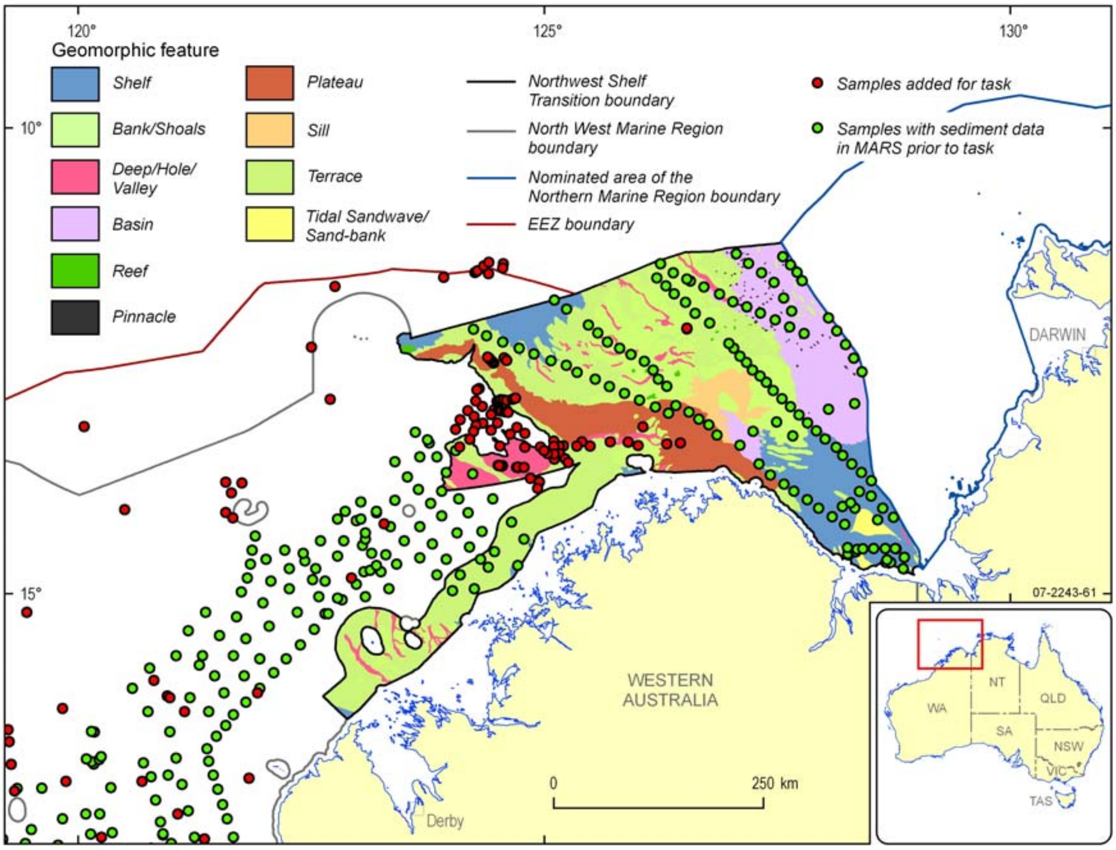
A total of 49 samples were collected from terraces, giving an average density of approximately 1:870 km^2. More than 50% of samples collected from terraces occur within a 50 km^2 area on the outer shelf near the boundary of the Timor Province. Remaining samples are distributed across the other terraces. The sample distribution means that not all sedimentary environments covered by the terrace are necessarily characteristic of all other terraces.

Banks/shoals contain 32 samples, giving an average density of 1:830km^2 for this feature. Deep/hole valleys contain 39 samples, giving an average density of 1:210 km^2. Sample distribution provides good coverage of all occurrences of these features in the NWST.

The Londonderry Rise contains 14 samples, giving an average density of 1:1,000 km^2. Samples are not distributed evenly across this feature but achieve sufficient coverage of the plateau to describe the sedimentology.

Basins contain 26 samples, giving an average density of approximately 1:760 km^2. Samples cover basins in the NWST, but they are more abundant in the deeper water areas of the Bonaparte Depression. These are the only basins containing adequate samples to describe the sedimentology (Fig. 5.16b).

Despite targeted sample addition, sample coverage is inadequate to assess sedimentology in pinnacles and tidal sand wave/sandbank features in the NWST. A total of 62 samples were added to this bioregion for this study, increasing coverage in deeps/holes/valleys (30), terraces (24), banks/shoals (4) and on the Londonderry rise (4).


120°
125°
130°
10°
15°
Geomorphic feature
Shelf
Bank/Shoals
Deep/Hole/
Valley
Basin
Reef
Pinnacle
Plateau
Sill
Terrace
Tidal Sandwave/
Sand-bank
Northwest Shelf
Transition boundary
North West Marine Region
boundary
Nominated area of the
Northern Marine Region boundary
EEZ boundary
Samples added for task
Samples with sediment data
in MARS prior to task
DARWIN
WESTERN
AUSTRALIA
Derby
0
250 km
07-2243-61
WA
NT
QLD
SA
NSW
VIC
TAS

a)

b)

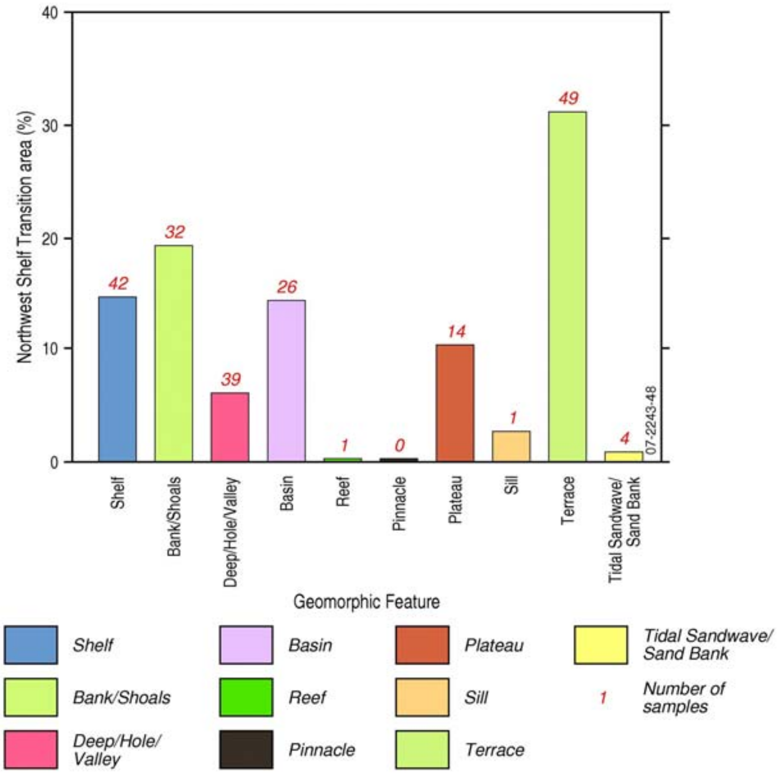
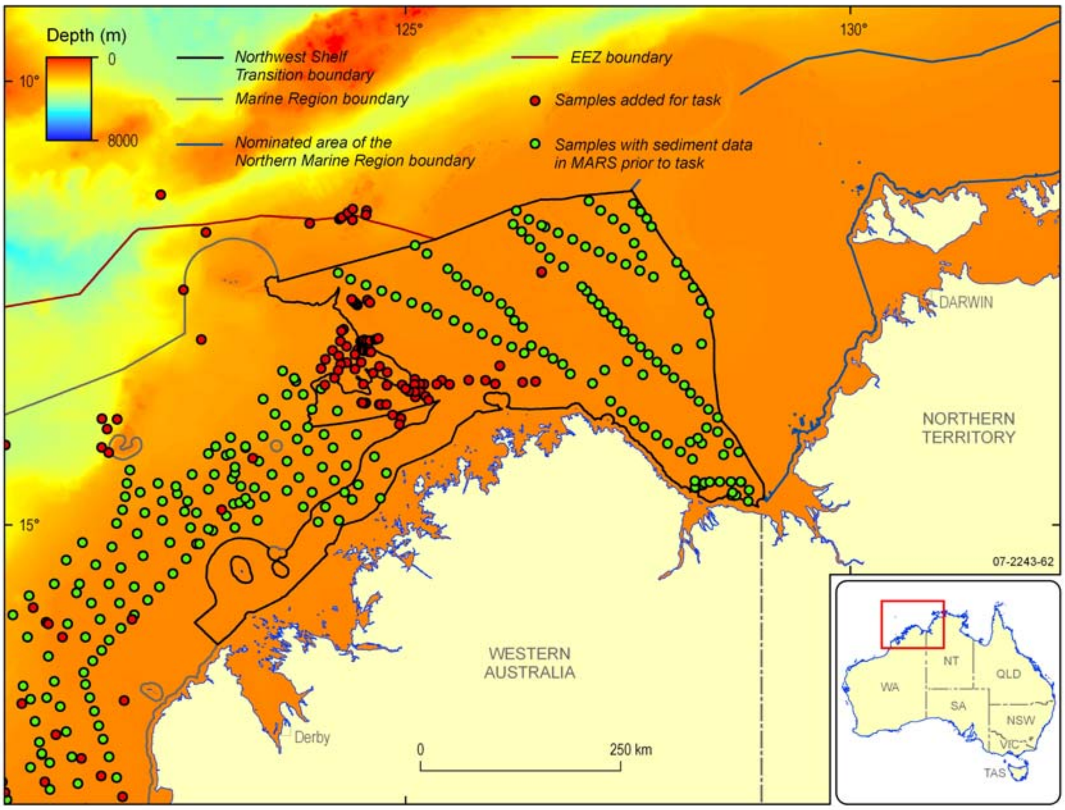


Figure 5.16. a) Geomorphology of the Northwest Shelf Transition (NWST) with location of sediment samples; and b) Percentage area of each geomorphic feature within the NWST with number of corresponding sediment samples.



a)

b)

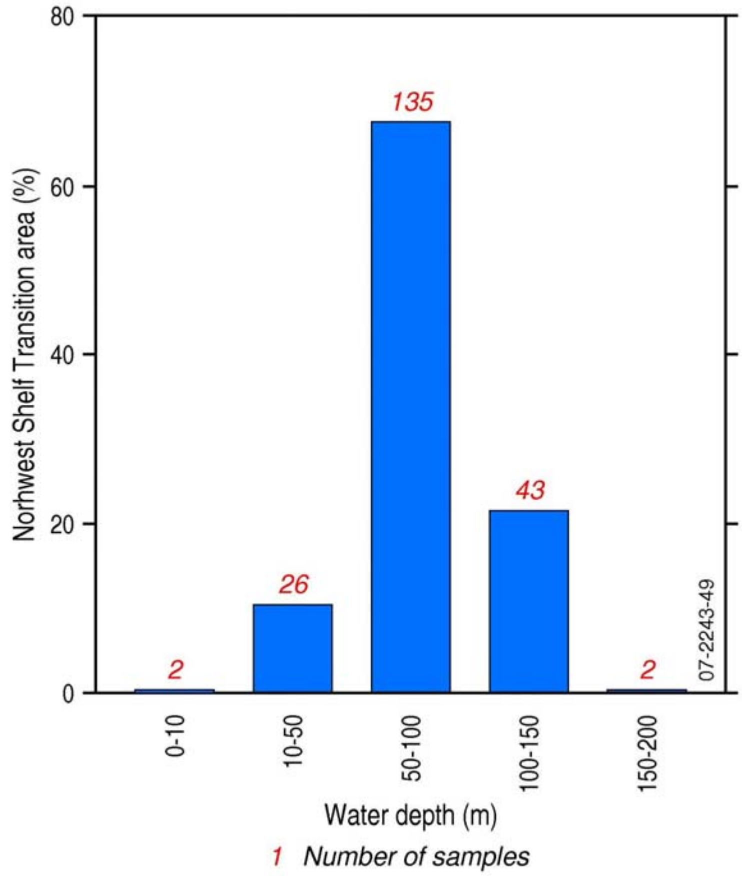


Figure 5.17. a) Bathymetry of the Northwest Shelf Transition (NWST) with location of sediment samples; and b) Percentage area of each bathymetry class within the NWST with number of corresponding sediment samples.

Table 5.8: Details of the geomorphology of the Northwest Shelf Transition.

Feature	**% of bioregion area covered**	**% of NWMR area this unit lies within this bioregion**	**% of EEZ area this unit lies within this bioregion**
Geomorphic Feature			
Unassigned shelf and slope	14.59	14.87	1.60
Bank/Shoals	19.34	90.94	52.33
Deep/Hole/Valley	5.97	8.74	4.94
Basin	14.45	100	2.97
Reef	0.26	17.21	0.77
Pinnacle	0.30	61.21	8.10
Plateau	10.27	14.91	0.94
Sill	2.72	100	21.44
Terrace	31.11	18.73	7.33
Tidal Sandwave/Sand Bank	0.99	100	5.64

Table 5.9: Distribution of water depths covered by the geomorphology in the Northwest Shelf Transition.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Unassigned shelf and slope	0 – 330	90
Geomorphic Feature		
Bank/Shoals	4 – 165	160
Deep/Hole/Valley	15 – 235	230
Basin	25 – 160	135
Reef	20 – 330	310
Pinnacle	25 – 165	140
Plateau	15 – 195	180
Sill	70 – 95	25
Terrace	10 – 235	230
Tidal Sandwave/Sand Bank	0 – 85	85

5.5.3. Sedimentology of the North West Shelf Transition

A total of 208 grain size assays and 194 carbonate assays occur in the NWST. Sediments in the east of the NWST differ significantly from those in the west. Within the Bonaparte Depression, sediments are variable but generally dominated by gravels closer to the coast, attaining up to 85% in four samples. Gravel content comprises <10% in five samples due to samples being located on top of tidal sand wave/sand bank features with similar sediment fractions (i.e. gravel <10%). Sand content is generally >50% in the Bonaparte Depression, with four samples attaining >90% sand. Mud content generally attains 20% within Bonaparte Depression but exceeds 50% in four samples located in close proximity to tidal sand wave/ sand bank features.

Sediments within the northern section of Bonaparte Depression are generally more homogenous and dominated by mud. Mud content is generally between 20 and 95%. A total of 15 of the 286 samples contain from 40 to 100% gravel due to proximity to the coast and to pinnacle features with similar sediment fractions (56 to 100% gravel).

In the west of the NWST, sediments contain between 25 and 90% sand. Sand comprises <20% in only one sample. These occur in deeps/holes/valleys features within 100 km of the coast. Mud is the next most abundant fraction with contents ranging from 5 to 52% in 80% of samples. Gravel content is generally between 0 and 33%, although it exceeds 50% in one sample that occurs in close proximity to deeps/holes/valleys and pinnacles.

Carbonate content exceeds 80% in 81 (42%) samples in the NWST. Throughout the Bonaparte Depression, carbonate contents of <20% are present locally. North of the Bonaparte Depression, carbonate content is generally <80%. Few carbonate assays are available for the textural size fractions, however those present indicate that carbonate content of sand in the NWST exceeds

80% in 144 (74%) samples. Carbonate content of gravel exceeds 90% for 54 (28%) samples. Carbonate content of mud is generally <80% but attains up to 90% in 15 samples.

5.5.4. Sedimentology of Significant Geomorphic Features

5.5.4.1. Sahul Shelf

A total of 42 samples were obtained from the shelf. Sediments in this feature are characterised by variable concentrations in mud, sand and gravel (Fig. 5.18f). Adjacent basin features show similar mud:sand ratios. Samples adjacent to reefs have increased gravel and sand fractions (40 to 75% and 20 to 90%, respectively). Bulk carbonate contents range from 13 to 88% with nine samples containing >50% (Fig. 5.19f). Carbonate sand ranges between 16 and 100% with 23 samples containing >50%.

5.5.4.2. Banks/shoals

A total of 32 samples were obtained from banks/shoals. Sediments in this feature are characterised by mud and sand with gravel present in samples adjacent to deeps/holes/valleys. Mud contents comprise 1 - 99% and >50% for 10 samples (Fig. 5.18a). Sand contents comprise 25 - 75% and >50% for 14 samples. Gravel contents generally attain 37%, with only three samples containing over 50%. At one location adjacent to deep/hole/valley and terrace features, the entire sample is composed of gravel clasts. Bulk carbonate content ranges between 21 and 98% and attains >50% in 24 samples (Fig. 5.19a). Carbonate sand ranges from 38 to 100% with 31 samples containing >50%.

5.5.4.3. Deep/hole/valleys

A total of 39 samples were obtained from deep/hole/valleys. Sand is the dominant fraction comprising between 15 and 80% with a total of 31 samples containing >50% sand (Fig. 5.18c). Mud is the next most dominant fraction with contents ranging between 9 and 83% and exceeding 50% in two samples. Two samples located adjacent to banks/shoal features contain between 80 and 85% mud. The remaining material in the sediments is gravel, ranging in content between 0 and 32% with a maximum of 35% where sand content is low. Bulk carbonate content ranges between 47 and 95%, with 30 samples containing >80% carbonate (Fig. 5.19c). Carbonate gravel ranges between 90 and 95% and attains 100% in three samples. Carbonate sand contents range from 67 to 100% and attains >80% in 34 samples. Carbonate mud contents range between 32 and 73% and attains >50% in 26 samples.

5.5.4.4. Basins

A total of 26 samples were obtained from outer-shelf basins. Mud is the dominant fraction and generally ranges between 9 and 97% with 15 samples containing >50% (Fig. 5.18b). Sand is the next most dominant fraction with contents ranging between 3 and 76% and five samples containing >50% sand content. Generally, samples adjacent to pinnacle features contain between 10 and 25% gravel contents. Bulk carbonate content generally ranges between 29 and 72%, with 13 samples containing >50% (Fig. 5.19b). Carbonate sand ranges between 27 and 100% and exceeds 90% in 20 samples.

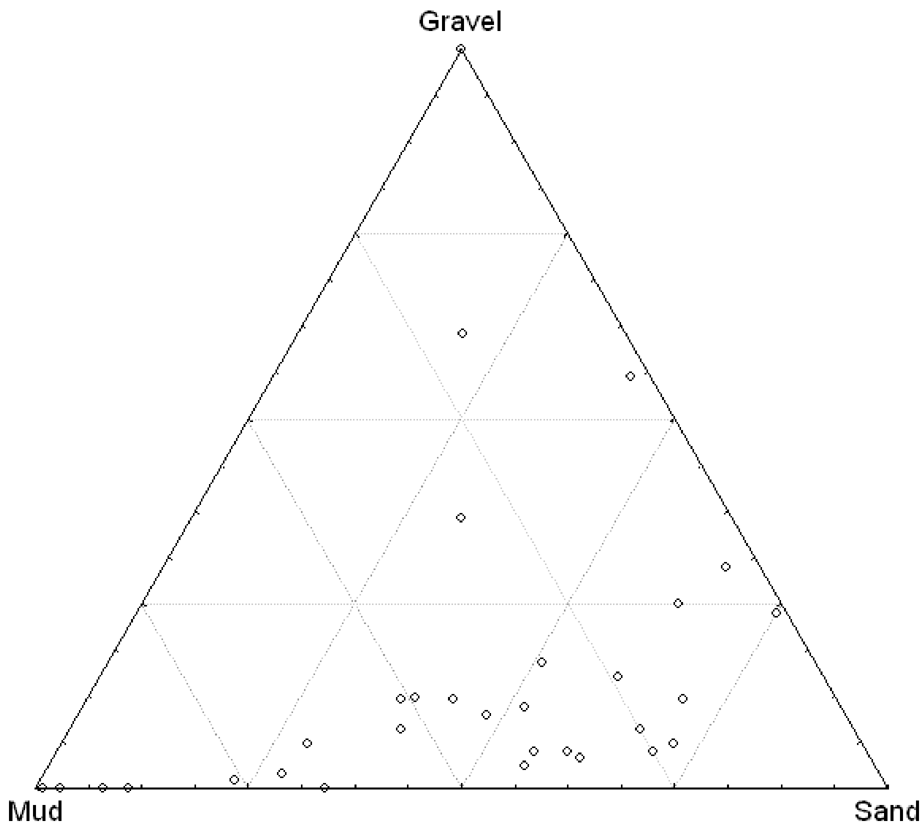
5.5.4.5. Londonderry Rise (plateau),

A total of 14 samples were obtained from plateaus. Sand is the dominant fraction, generally ranging from between 32 and 85% with 11 samples attaining >50% (Fig. 5.18d). Mud is the next most abundant fraction with contents attaining 44% and four samples attaining >30%. Gravel content is consistently <22%, although one sample adjacent to terrace and basin features contained 62% gravel. Bulk carbonate content ranges between 17 and 93% with nine samples containing >50% (Fig. 5.19d). Carbonate sand ranges from 14 to 99% with 10 samples containing >50%.

5.5.4.6. Terraces <300 m Water Depth

A total of 49 samples were obtained from terraces. Sand is the dominant fraction generally ranging between 16 and 89% with 36 samples containing >50% (Fig. 5.18e). The remaining material is mud, which ranges in content between 5 and 84%. Gravel contents of <39% occur across the NWMR, although five samples, collected from areas adjacent to banks/shoals, contain no gravel. Bulk carbonate content generally varies between 48 and 95% with 44 samples containing >50% carbonate (Fig. 5.19e). Carbonate sand content ranges between 92 and 100% with four samples attaining 100%. Carbonate mud content ranges between 44 and 90% with 18 samples exceeding 50%. Carbonate gravel content ranges between 90 and 100% with seven samples attaining 100%.

a)



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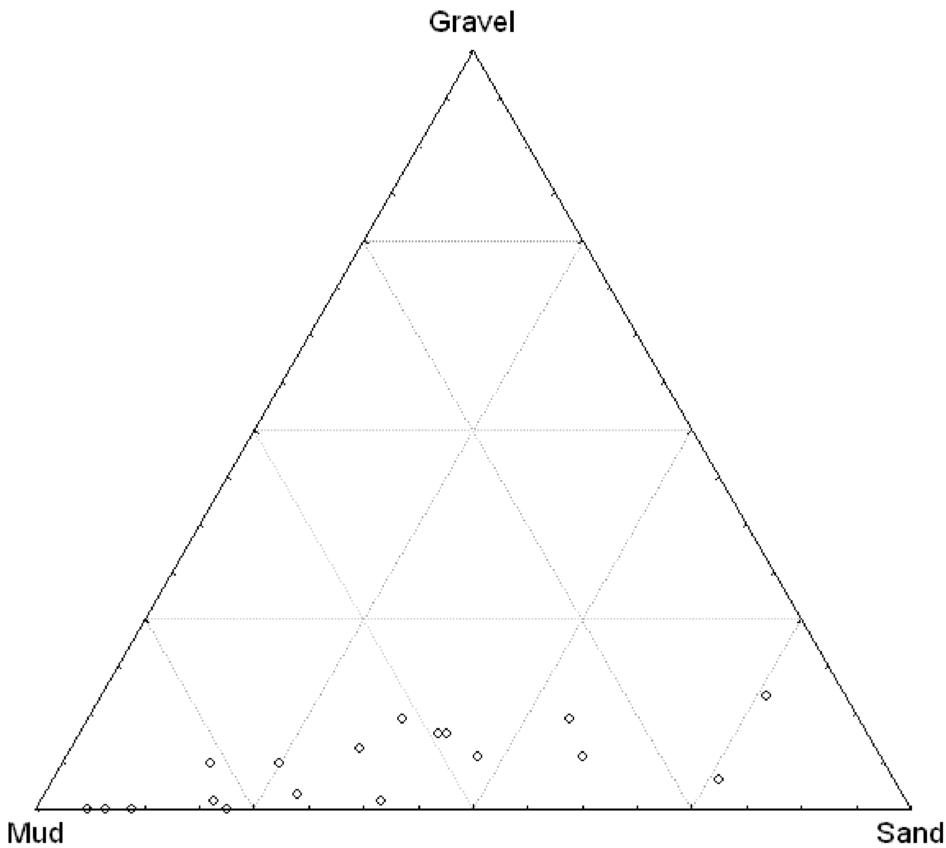

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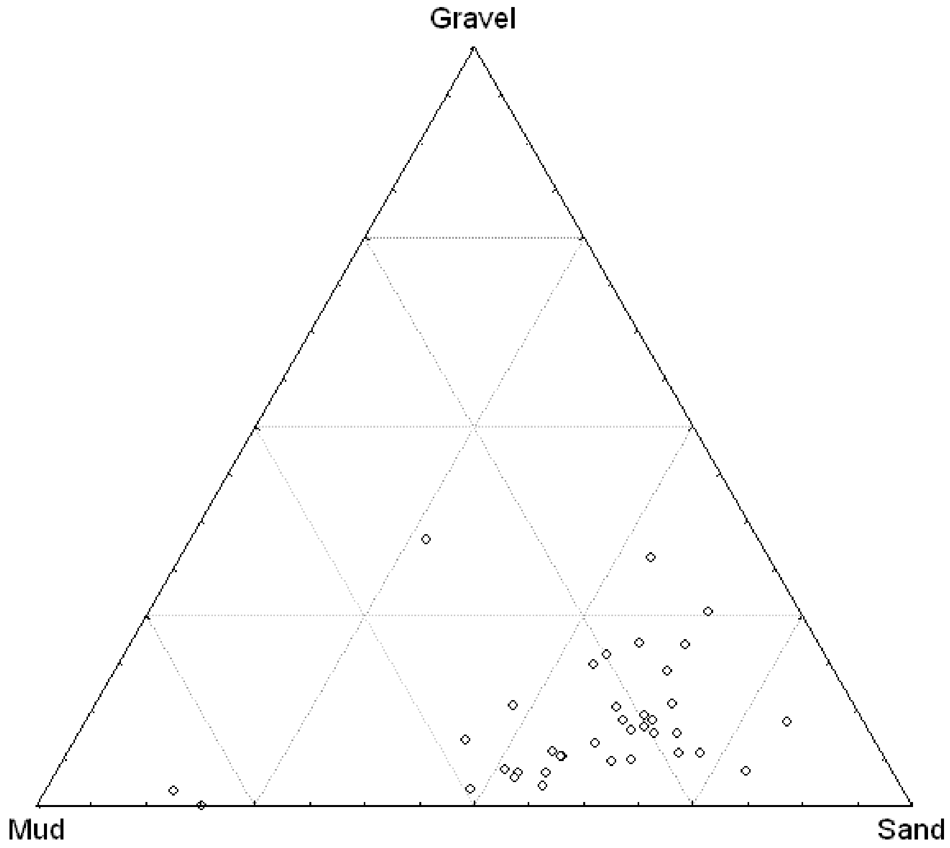

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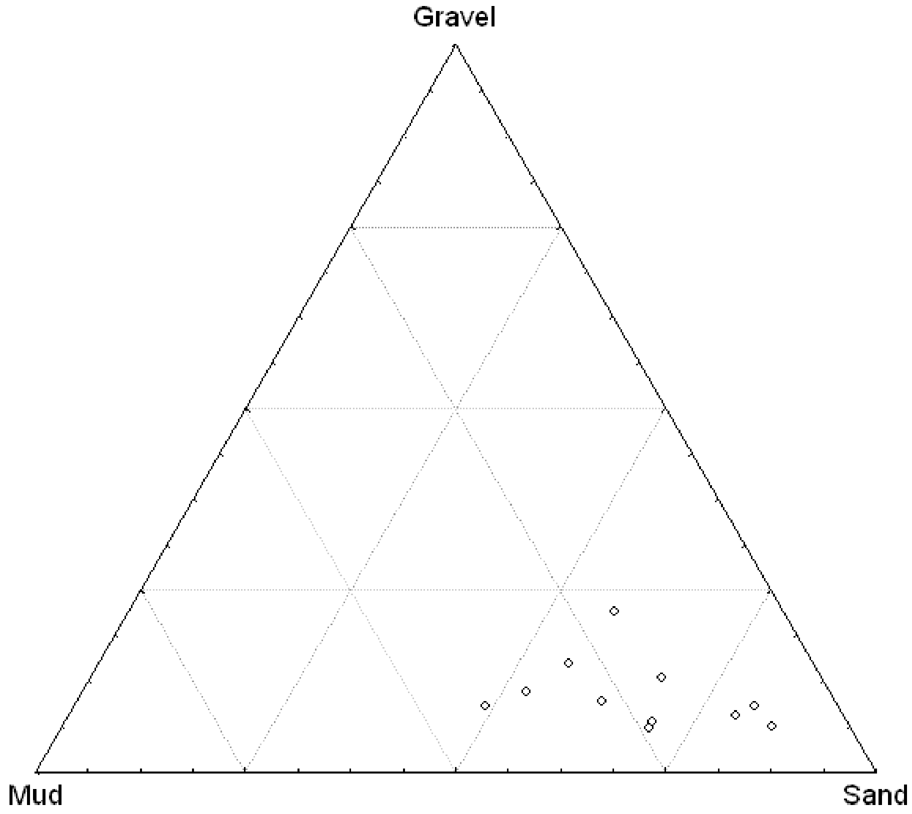

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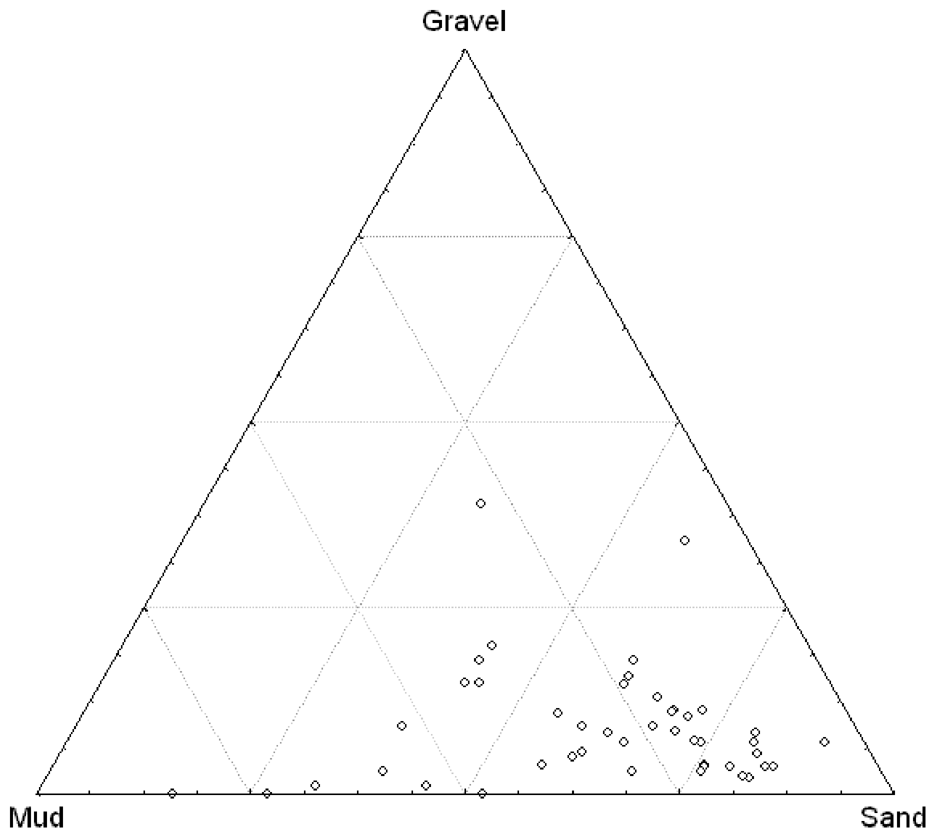

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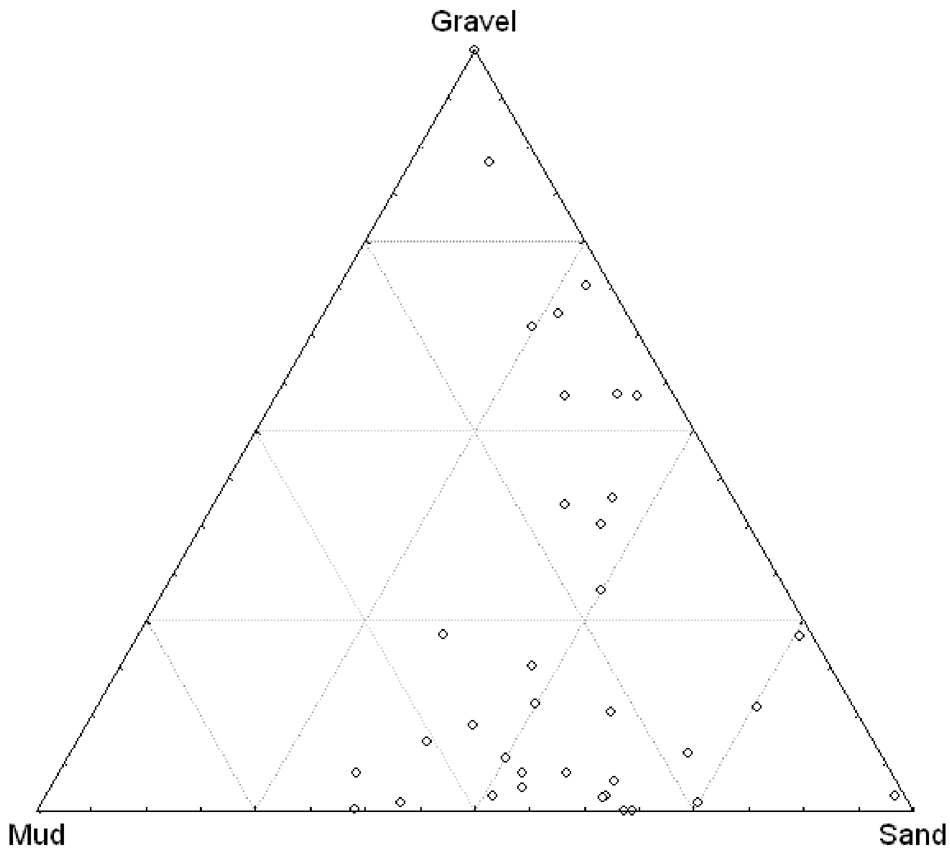
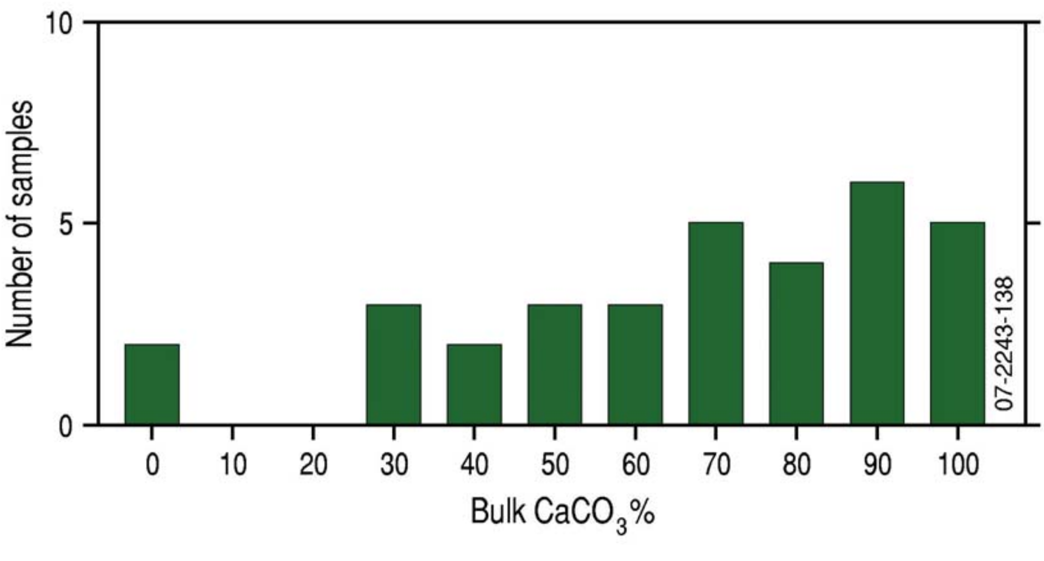
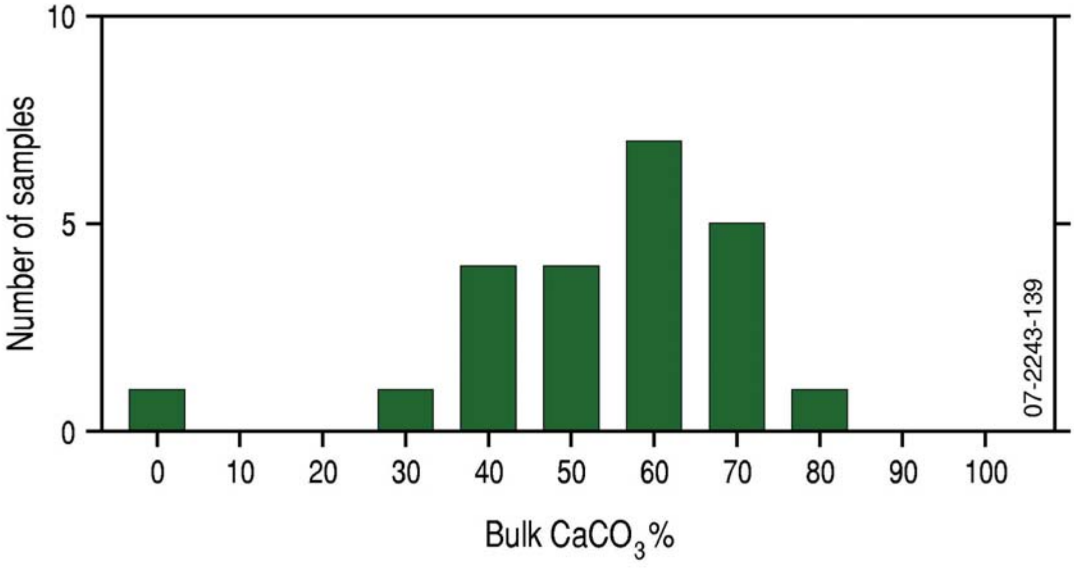


Figure 5.18. Textural composition (mud:sand:gravel ratio) of a) bank/shoal; b) basin; c) deep/hole/valley; d) plateau; e) terrace; f) shelf sediments within the NWST.

a)



b)


10
5
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Number of samples
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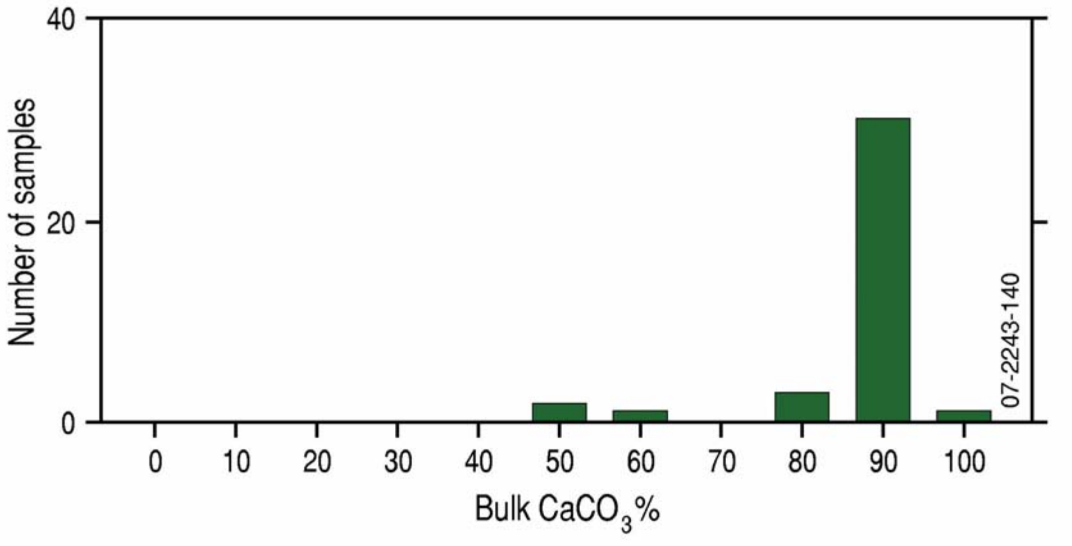
100
Bulk $CaCO_3$%
07-2243-139

c)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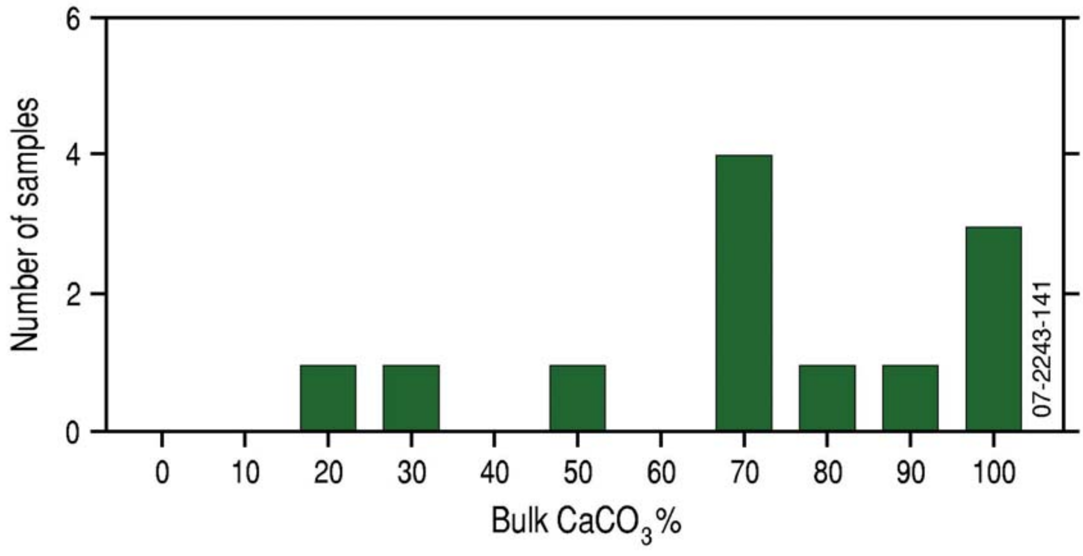
07-2243-140

d)



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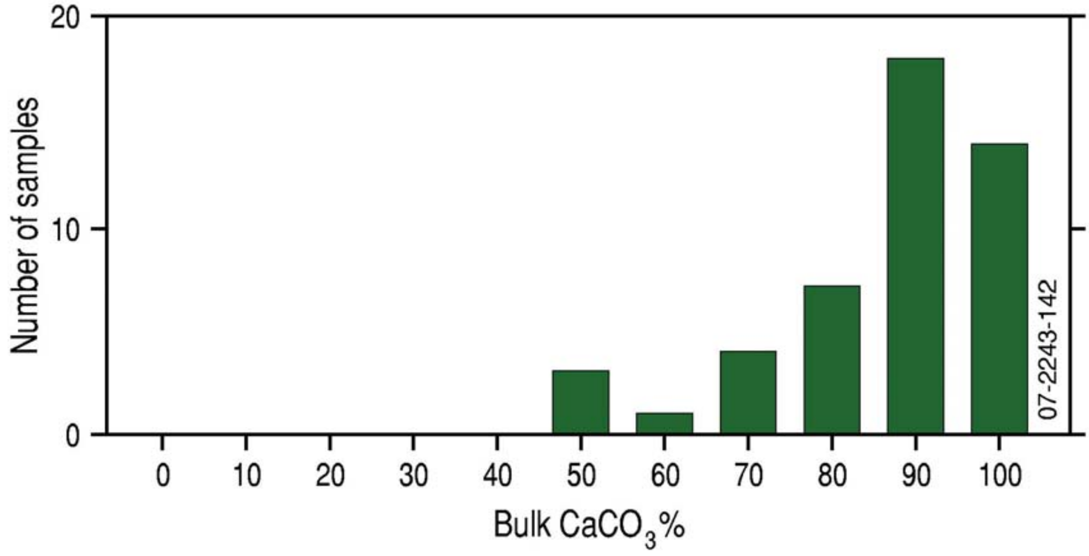

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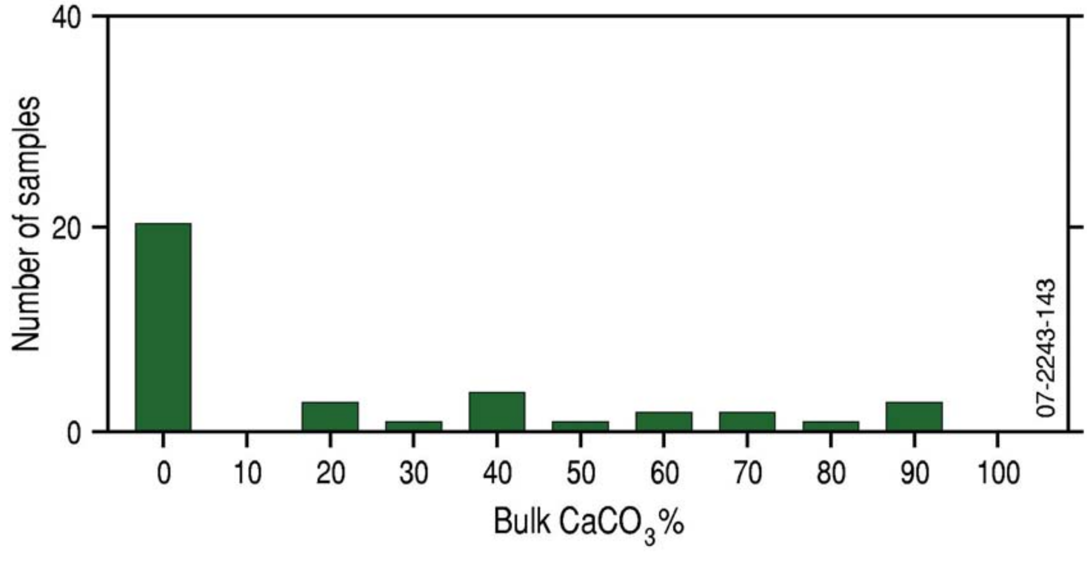


Figure 5.19. Carbonate content of a) bank/shoal; b) basin; c) deep/hole/valley; d) plateau; e) terrace; and f) shelf sediments within the NWST.

5.6. TIMOR PROVINCE (TP)

5.6.1. Geomorphology and bathymetry

The Timor Province (TP) covers a total area of 178,650 km^2, all of which occurs in the NWMR (Fig. 5.1). This bioregion represents 15% of the total area of the NWMR (Table 5.1). The TP is located on the slope, between Broome and Cape Bouganville (Fig 5.20a). It is separated from the coast to the east by the NWSP and NWST, bounded to the south by the NWT, and separated from EEZ boundary to the west by the area of the EEZ not allocated to a bioregion.

Water depths in the bioregion range from 10 m near the shelf break to 5,920 m on the Argo Abyssal Plain (Fig 5.21a). A total of 38% of the area occurs in depths of <500 m and 14% in depths of >5,000 m (Fig. 5.21b; Table 5.11).

The TP is dominated by slope (unassigned) (50,170 km^2, 32%) and terraces (47,510 km^2, 30%). Significant areas are covered by plateaus (18,500 km^2, 12%), abyssal plain/deep ocean floor (unassigned) (17,990 km^2, 12%) and deeps/holes/valleys (12,540 km^2, 8%). Rise, canyons, reefs, aprons/fans, knolls/abyssal hills/peaks and pinnacles are present, but each cover <4,500 km^2 (3%) of the total bioregion area (Table 5.10).

A total of four significant features have been identified that characterise the TP. These have the potential to contain sedimentary environments not found elsewhere in the NWMR or EEZ due to the water depth and oceanographic setting of the region (as described in Section 3). Slope (unassigned) is judged significant as it forms the largest area of any feature in this region and varies in sedimentology from adjacent areas of slope due to a high gravel component (Fig. 5.23c). Small terraces on the upper slope cover approximately 5,670 km^2 (4%) of the bioregion area; however, they represent a larger proportion of all shallow water terraces found in the NWMR (5,670 km^2, 14%). These form the northernmost extent of a string of terraces with similar morphology, bathymetry and tectonic origin that extend across the TP and NWT to the south.

Reefs in the TP are considered significant as they form almost half of the total area of reefs in the NWMR. Reefs north of Ashmore Reef are likely to differ from reefs in elsewhere in the NWMR as they are dominated by algae while reefs occurring to the south are dominated by hard corals (Chapter 3). Aprons/fans are generally associated with the reefs and cover less than 1% of the area of the TP, however this area forms >45% of the total area of aprons/fans in the NWMR.

Terraces located in deeper water cover a far larger area of the bioregion (~55%), including approximately 60% of the Rowley Terrace. The remainder of this feature is located to the south in the NWT where sample coverage is adequate to describe the sedimentology of this feature. Deepwater Terraces in the NWMR contain relatively homogenous sedimentology (Chapter 4), and therefore no additional sediment information can be provided by the analysis of these features at a bioregion scale. Likewise, Scott Plateau and the Argo Abyssal Plain each cover 11% of the bioregion, but relatively homogeneous sedimentology observed across all these features at a NWMR scale means no additional sediment information can be provided by an analysis at a bioregion scale.

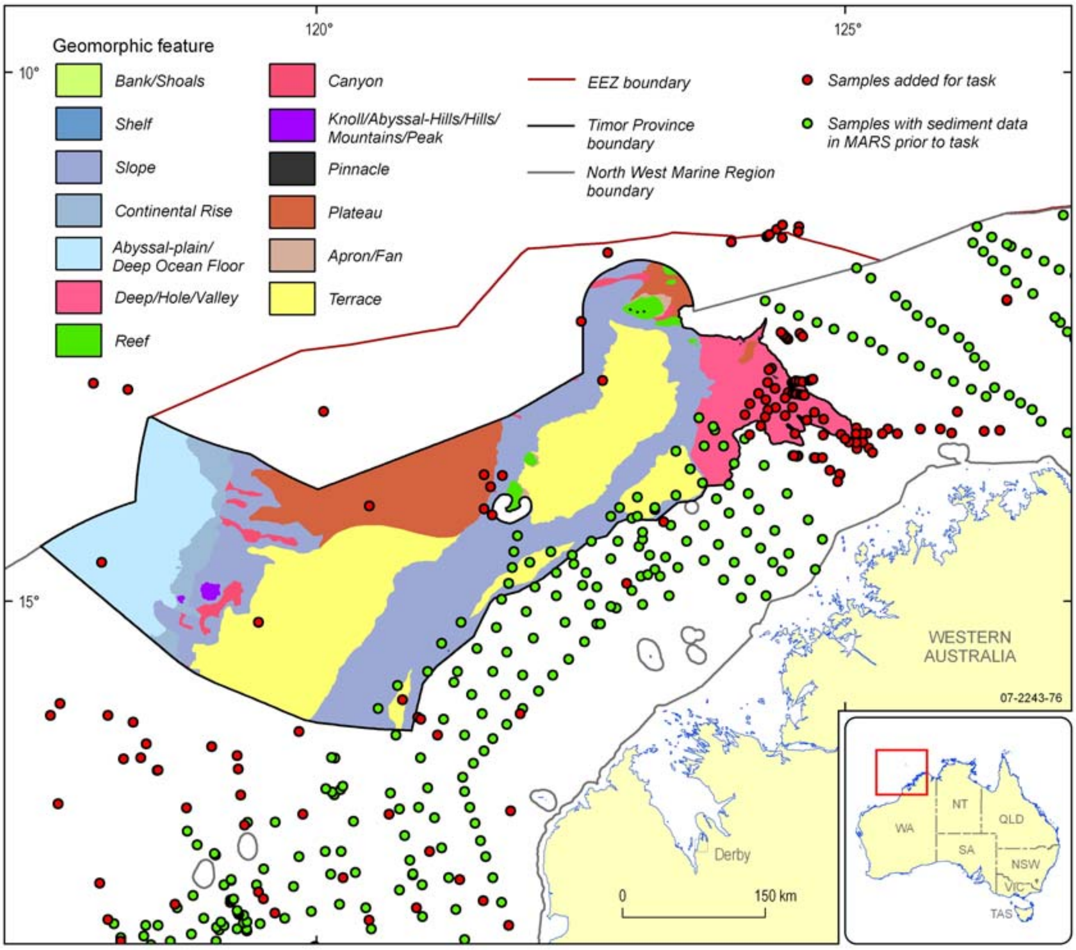
5.6.2. Sample Coverage

The TP is represented by 77 samples (Figs. 5.20a). More than 50% (39) of these are located on the upper slope near the shelf break and some within water depths <500 m and within 250 km of the coast. The remaining samples are distributed across the lower slope with one point on the AP/DOF in water depths >5,000 m.

Average sample density across the assessed area of the bioregion is >1:2,000 km^2, however sample densities are generally higher than this on the upper slope (<200 m water depth) and lower in deep water.

Samples achieve adequate coverage to describe the sedimentology in three of the four significant features identified for this bioregion. A total of 14 samples were collected from the area of the slope (unassigned), giving an average density of approximately 1:3,580 km^2. Clustering of samples means that assays are likely to best represent sediment types present on the upper slope. A total of 15 samples were collected from three terraces on the upper slope, giving an average density of approximately 1:3,170 km^2. A total of 41 samples were collected from deeps/holes/valleys, giving an average density of approximately 1:310 km^2.

Despite targeted sample addition, an insufficient number of samples were collected from reefs and aprons/fans in the TP to describe their sedimentology. One sample was collected from reefs and no samples from aprons/fans were available for procurement for this study. Sedimentology of reefs is discussed in Chapters 3 and 6 from results of previous studies. 42 samples were added to the TP for this study. These increased sample coverage in the slope (unassigned) (3 samples added), terrace (2) and deeps/holes/valleys (31) features.



120°
125°
10°
15°
Geomorphic feature
Bank/Shoals
Shelf
Slope
Continental Rise
Abyssal-plain/
Deep Ocean Floor
Deep/Hole/Valley
Reef
Canyon
Knoll/Abyssal-Hills/Hills/
Mountains/Peak
Pinnacle
Plateau
Apron/Fan
Terrace
EEZ boundary
Timor Province
boundary
North West Marine Region
boundary
Samples added for task
Samples with sediment data
in MARS prior to task
WESTERN
AUSTRALIA
07-2243-76
Derby
0
150 km
NT
QLD
WA
SA
NSW
VIC
TAS

a)

b)

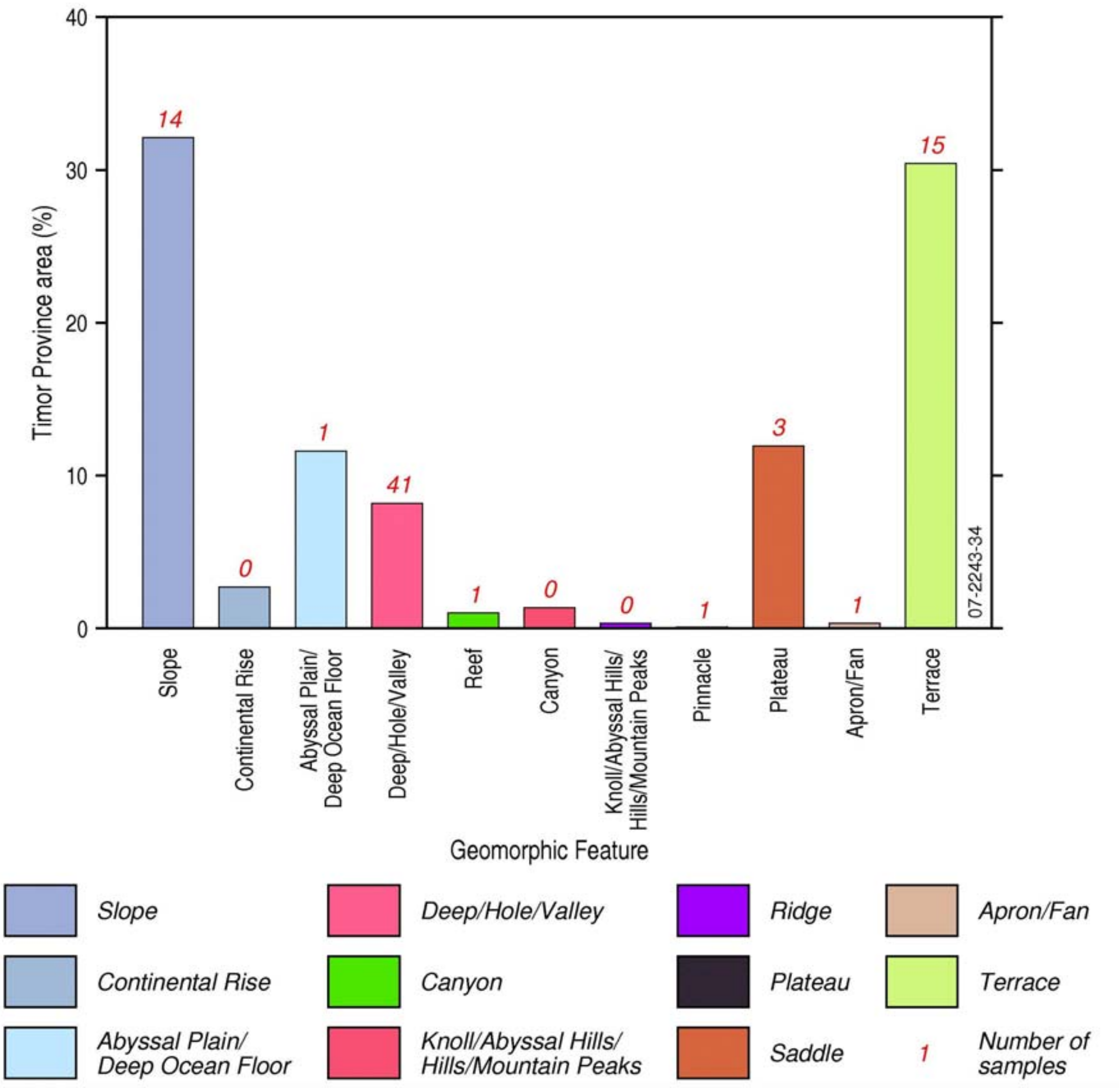
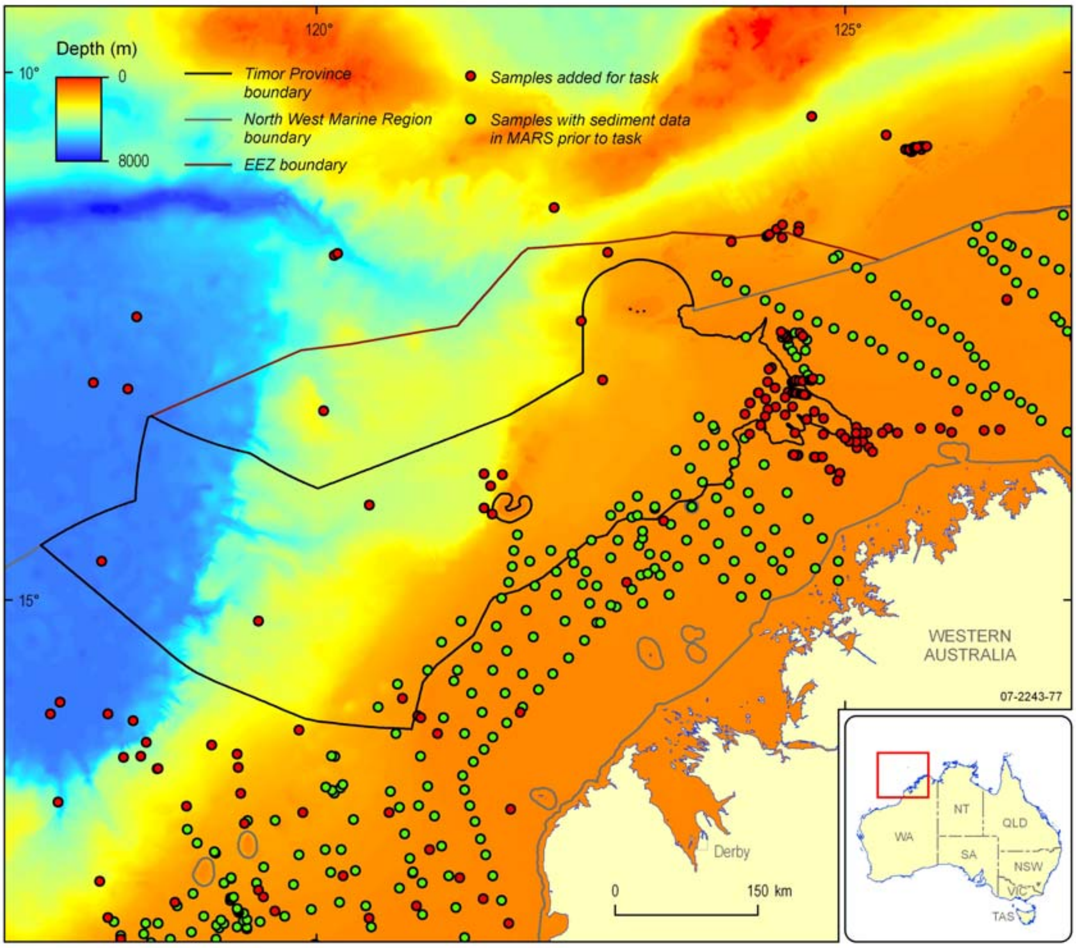


Figure 5.20. a) Geomorphology of the Timor Province (TP) with location of sediment samples; and b) Percentage area of each geomorphic feature within the TP with number of corresponding sediment samples.

a)



b)

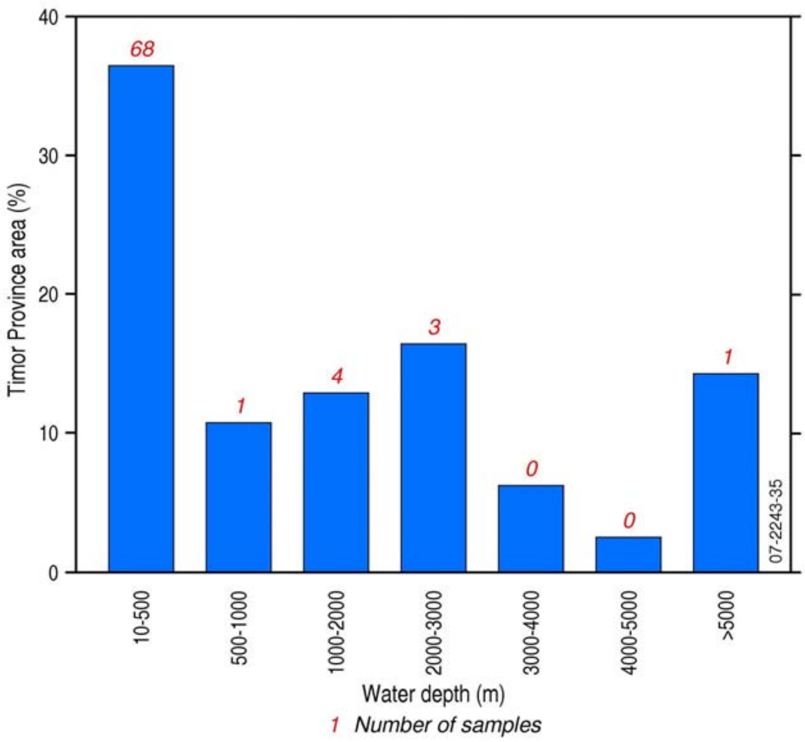


Figure 5.21. a) Timor Province showing bathymetry with location of sediment samples; and b) Percentage area of each bathymetry class within the TP with number of corresponding sediment samples.

Table 5.10. Details of the geomorphology of the Timor Province.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Province			
Slope	85.56	20.60	3.33
Rise	2.90	28.56	4.43
AP/DOF*	11.54	17.98	0.62
Geomorphic Feature			
Slope (unassigned)	32.18	16.15	3.65
Rise (unassigned)	2.90	28.56	4.72
AP/DOF* (unassigned)	11.54	18.23	0.73
Deep/hole/valley	8.04	13.44	7.59
Reef	1.028	76.58	3.44
Canyon	1.47	21.20	2.14
Knoll/abyssal hills/mountains/peak	0.23	17.59	0.30
Pinnacle	0.04	9.59	1.27
Plateau	11.87	19.66	1.24
Apron/fan	0.23	49.39	3.11
Terrace	30.48	20.93	8.20

Table 5.11. Distribution of water depths covered by the geomorphology in the Timor Province.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
AP/DOF	4,570 – 5,920	5,615
Slope	35 – 5,660	1,315
Continental rise	4,035 – 5,635	5,225
Geomorphic Feature		
Slope (unassigned)	95 – 5,650	5,560
Rise (unassigned)	4,035 – 5,635	5,225
AP/DOF (unassigned)	4,570 – 5,920	5,615
Deep/hole/valley	45 - 275	235
Reef	35 – 1,325	1,360
Canyon	95 – 5,660	5,565
Knoll/abyssal hils/mountains/peak	3,170 – 5,605	2,435
Pinnacle	5 - 295	290
Plateau	35 – 3,440	3,410
Apron/fan	5 – 375	375
Terrace	215 – 3,685	3,470

5.6.3. Sedimentology of the Timor Province

The TP contains 77 grainsize and 70 carbonate assays. Approximately 45 (58%) of these samples occur within 100 km of the shelf break. Sediment texture in this area is highly variable (Fig. 5.22). Sand content comprises 10 to 100% of sediment. Mud content ranges from <1 to 80%, but mud was <1% in 3 samples and >50% in 13 (17%) samples. Gravel exceeds 50% in only two samples and comprises <1% in 32 (42%) samples. Sand contents of <50% occur within 100 km from the shelf break within the area of the Browse Depression.

Samples are distributed more sparsely over the rest of the slope in the bioregion, and a single sample occurs on the AP/DOF. Sand content in these areas is significantly lower than near the shelf break, ranging from 0 to 56%, and exceeding 50% in only one sample. Mud content is generally higher near the abyssal plain/deep ocean floor, ranging from 44 to 99% and attaining >60% in all but one sample. Gravel is generally absent. The single sample from the Argo Abyssal Plain contains 99% mud.

Carbonate in the TP decreases with increasing water depth. Carbonate content within 100 km of the shelf break is regularly >60% and >80% in 61 (87%) samples. In the rest of the bioregion, carbonate content ranges from <1% on the AP/DOF to just under 80% on the slope in the north. Sediments on the mid to lower slope contain between 40 and 80% carbonate.

Carbonate gravel and sand contents attain >80%. Carbonate mud ranges from 50 to 91%, although samples with this information cover only a small area of the bioregion near the shelf break.

5.6.4. Sedimentology of Significant Geomorphic Features

5.6.4.1. Slope

A total of 14 samples were obtained from the slope. Sediments in this feature are characterised by large variations between sand:mud ratios (Fig. 5.22c). Sand content ranges between 12 and 92% with seven samples containing >50% sand. Mud content generally ranges from 24 to 87% with seven samples containing >50% mud. Gravel contents attain 18%, although one sample attains 47% where mud concentration is low. Bulk carbonate content generally ranges from 67 to 92% with five samples comprising >80% (Fig. 5.23c).

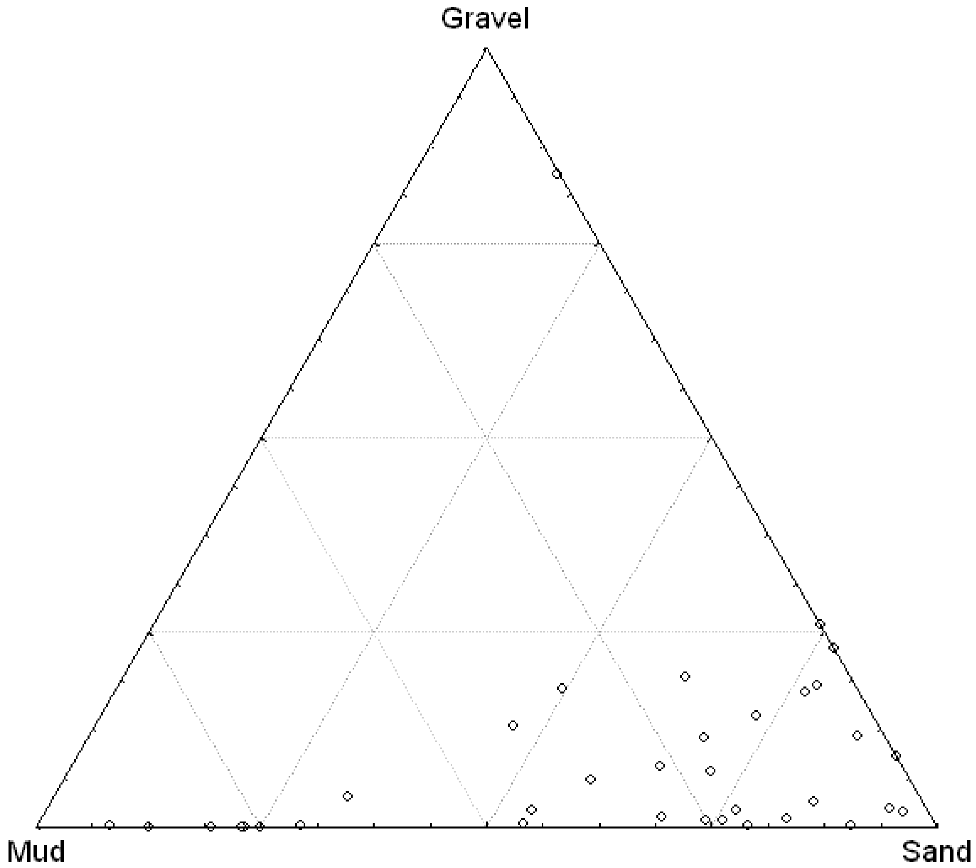
5.6.4.2. Small Upper Slope Terraces

A total of 15 samples were obtained from upper slope terraces. Sand is the dominant fraction comprising between 9 and 100% with 12 samples containing >50% sand (Fig. 5.22b). Mud content ranges from 4 to 77% with four samples attaining contents >50%. Gravel content ranges from 1 to 40%. Adjacent slope and deeps/holes/valleys contain sediments with similar textural properties. Bulk carbonate content generally varies between 63 and 95% with eight samples attaining >80% (Fig. 5.23b).

5.6.4.3. Deep/hole/valley

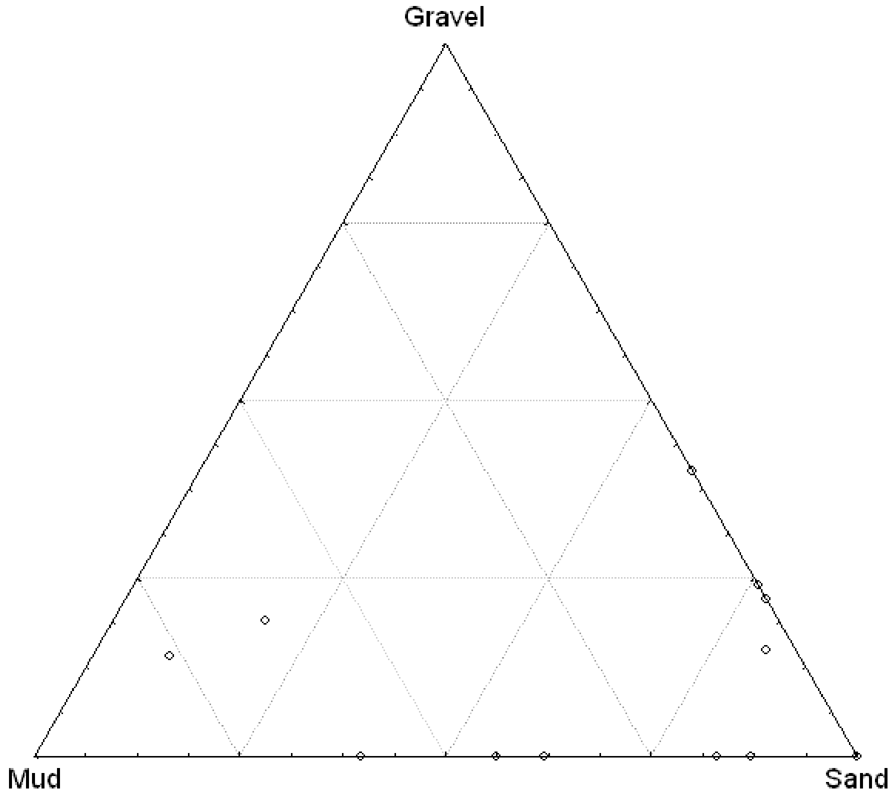
A total of 41 samples were obtained from deeps/holes/valleys. Sand is the dominant fraction comprising between 8 and 100% with 25 samples attaining contents exceeding 50% (Fig. 5.22a.).

Mud content ranges from <1 to 92% with eight samples attaining contents >50%. Gravel content varies between <1 to 26% but attains 84% in one sample. Bulk carbonate content generally ranges between 65 and 99% with 24 samples exceeding 50% (Fig. 5.23a.). Carbonate sand varies from 81 and 97% and attains >80% in 23 samples. Carbonate mud varies between 58 and 91% and exceeds 80% in five samples. Carbonate gravel ranges from 90 and 100% and attains 100% in 16 samples.



a)

b)



c)

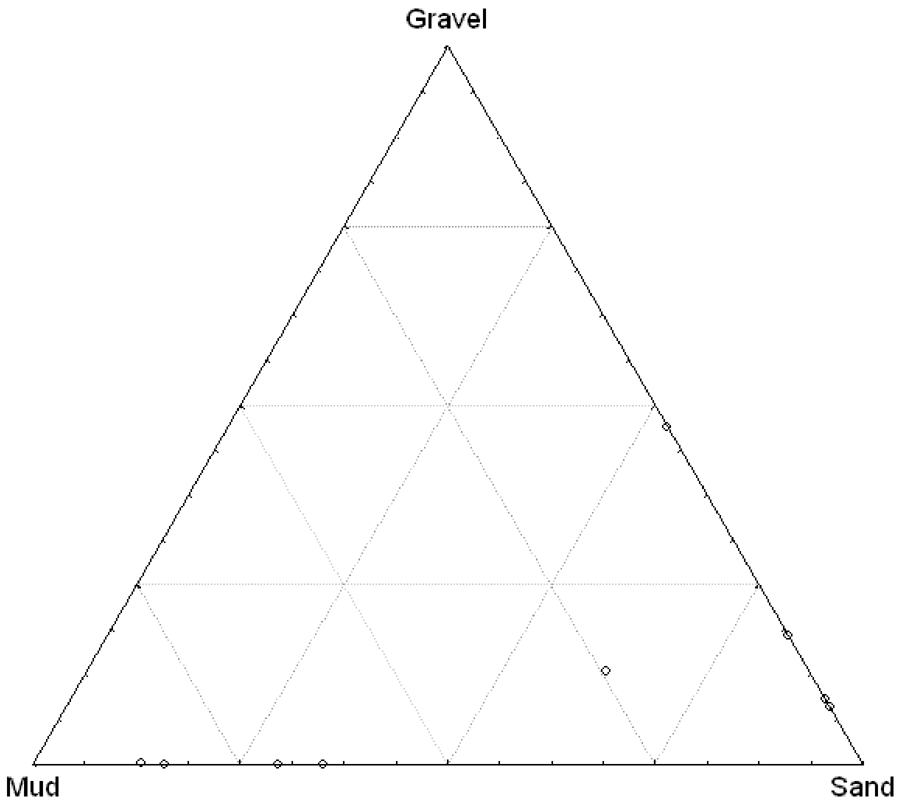


Figure 5.22. Textural composition (mud:sand:gravel ratio) of a) deep/hole/valley; b) terrace; and c) slope sediments within the TP.

a)

b)

c)

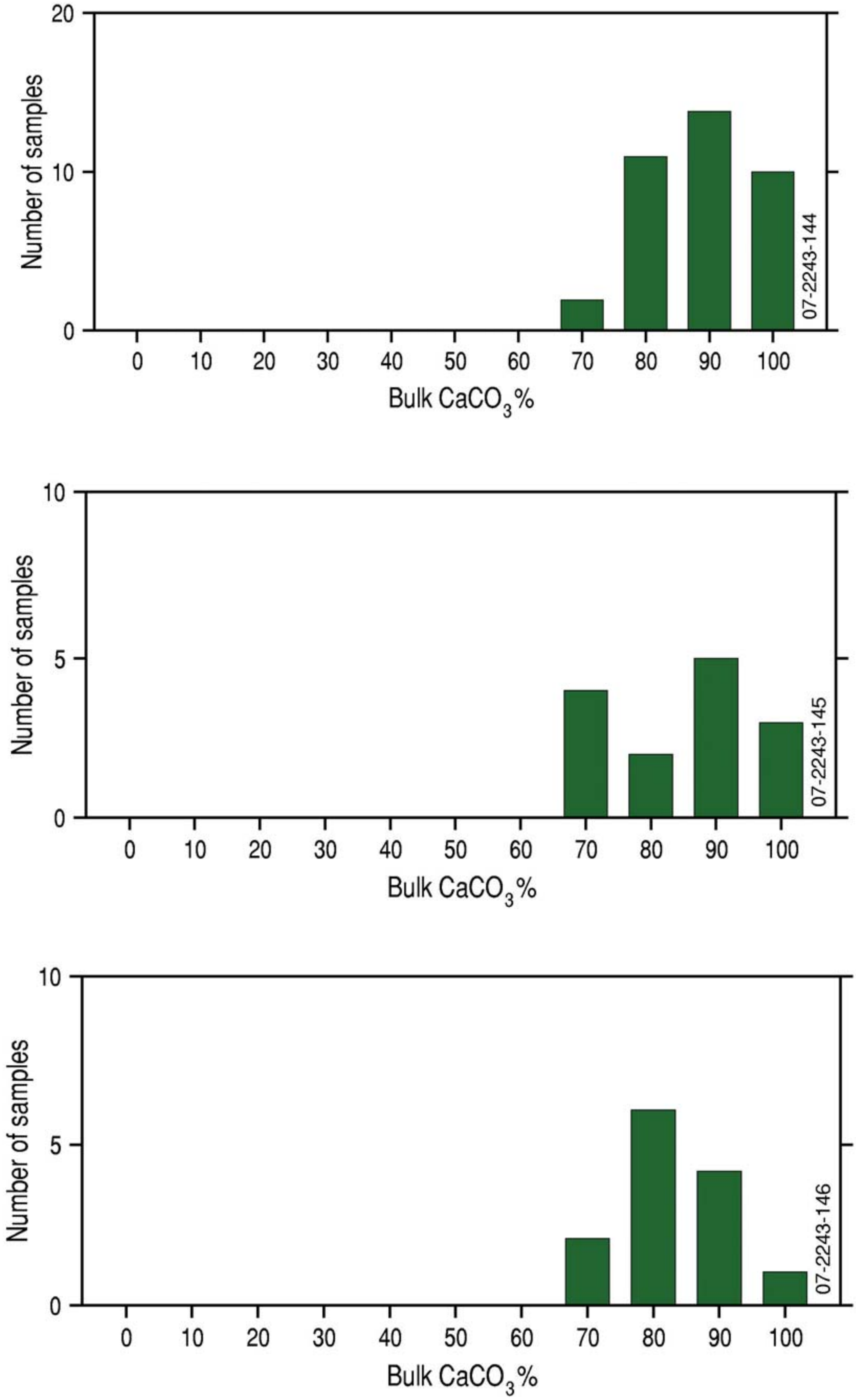


Figure 5.23. Carbonate content of a) deep/hole/valley; b) terrace; and c) slope sediments within the TP.

5.7. NORTHWEST TRANSITION (NWT)

5.7.1. Geomorphology and bathymetry

The Northwest Transition (NWT) covers a total area of 183,550 km², all of which is situated in the NWMR (Fig 5.1). This bioregion represents 17% of the total area of the NWMR (Table 5.1). The NWT is located off the shelf between the Dampier Archipelago and Lacepede Island. It is separated from the coast by the NWSP and extends to the EEZ boundary in the west. It is bounded to the south by the Northwest Province and to the north by the TP.

A total of 96,360 km² (53%) of the NWT occurs on the slope (Fig 5.24b; Table 5.12). Smaller areas in the northwest of the region are located on the Argo Abyssal Plain (40,650 km², 22%) and rise (3,800 km², 2%). The eastern boundary is coincident with the shelf break. Water depths in the bioregion range from 10 m near the shelf break to approximately 5,980 m on the Argo Abyssal Plain (Fig 5.25a). Water depths vary greatly across the bioregion with 34% of the area occurring in depths of <500 m and 21% in depths of >5,000 m. (Fig. 5.25 a& b).

The NWT contains similar geomorphology to the adjacent TP and features such as the Argo Abyssal Plain and Rowley Terrace straddle the boundary between them. The NWT is dominated by slope (unassigned) (96,360 km², 53%), followed by terraces (38,420 km², 21%) and abyssal plain/deep ocean floor (40,650 km², 22%). Other geomorphic features include: rise, ridges, canyons, deeps/holes/valleys, knolls/abyssal hills/peaks, aprons/fans, reefs and saddles each cover <4,000 km² (2%) (Table 5.12).

A total of eight significant features have been identified for the NWT. Slope (unassigned) forms 96,360 km² (52%) of the NWT and is likely to be characterised by different physical attributes from slope in adjacent bioregions because large areas of it lie in deepwater (>4,000 m) adjacent to the Argo Abyssal Plain.

The NWT contains >60% of the area of the Argo Abyssal Plain in the NWMR. This represents 41% of the total area of AP/DOF in the NWMR. This feature has a geological history and morphology that differs from areas of abyssal plain/deep ocean floor elsewhere in the NWMR and has influenced sediment deposition in this area (Chapter 3).

Terraces on the upper slope are a continuation of similar features in the TP. These features cover an area of approximately 22,900 km² or 11% of the NWT. Individual features in the NWT are generally larger than those in the TP. Five terraces, each exceeding 10,000 km² in area, occur in deepwater and cover approximately 27,900 km² or 13% of the NWMR. This area includes the southern half of the Rowley Terrace. These features have been shown to have homogeneous sedimentology at a NWMR scale (Chapter 4), and therefore no information can be added by analysis at a planning region scale.

Reefs of the Rowley Shoals comprise 12% of the total area of this feature in the NWMR, and are known to differ from hard-coral reefs occurring elsewhere in the NWMR by their bathymetry, with significant areas occurring in water depths >150 m. Aprons/fans, ridges, knolls and rise in the NWT form significant portions of the total NWMR area for these features.

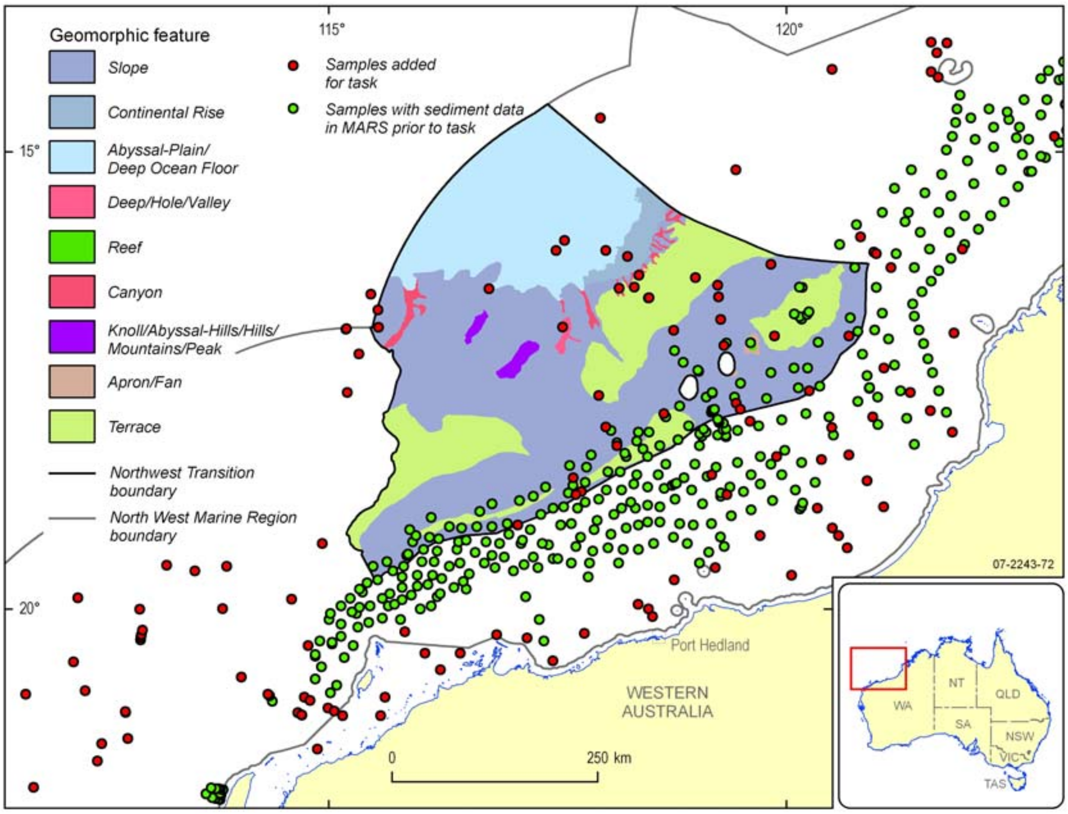
5.7.2. Sample Coverage

The NWT is represented by 125 samples (Figs. 5.24a). More than 75% of samples occur on the upper slope within 100 km of the shelf break and in <500 m water depth (Fig. 5.25a). Remaining samples occur on the slope, rise and AP/DOF in the northern half of the bioregion. These provide coverage of water depths ranging from 500 to >5,000 m.

Average sample density across the bioregion is approximately 1:1,450 km^2. A total of 88 (70%) samples occur on areas of the slope (unassigned) resulting in an average density of approximately 1:1,100 km^2 in this feature. Terraces contain 31 (25%) samples resulting in an average density of approximately 1:1,240 km^2. AP/DOF contains three samples (<1%) giving an average density of 1:13,550 km^2.

Samples achieve adequate coverage to describe the sedimentology in three of the eight significant features identified for this bioregion. Details of coverage of the slope and Argo Abyssal Plain are given above.

Despite targeted sample addition, not enough samples were collected from reefs, aprons/fans, knolls and continental rise in the TP to describe the sedimentology in these features. A total of 34 samples were added to the NWT for this study. These increased sample coverage on the slope (unassigned) (22 samples added), the Argo Abyssal Plain (3), rise (1) and terrace (5). No samples collected from reefs, aprons/fans or knolls were available for procurement. Sedimentology of these features is discussed in Chapters 3 and 6.


Geomorphic feature
Slope
Continental Rise
Abyssal-Plain/
Deep Ocean Floor
Deep/Hole/Valley
Reef
Canyon
Knoll/Abyssal-Hills/Hills/
Mountains/Peak
Apron/Fan
Terrace
Northwest Transition
boundary
North West Marine Region
boundary
Samples added
for task
Samples with sediment data
in MARS prior to task
115°
120°
15°
20°
Port Hedland
WESTERN
AUSTRALIA
0
250 km
07-2243-72
WA
NT
QLD
SA
NSW
VIC
TAS

a)

b)

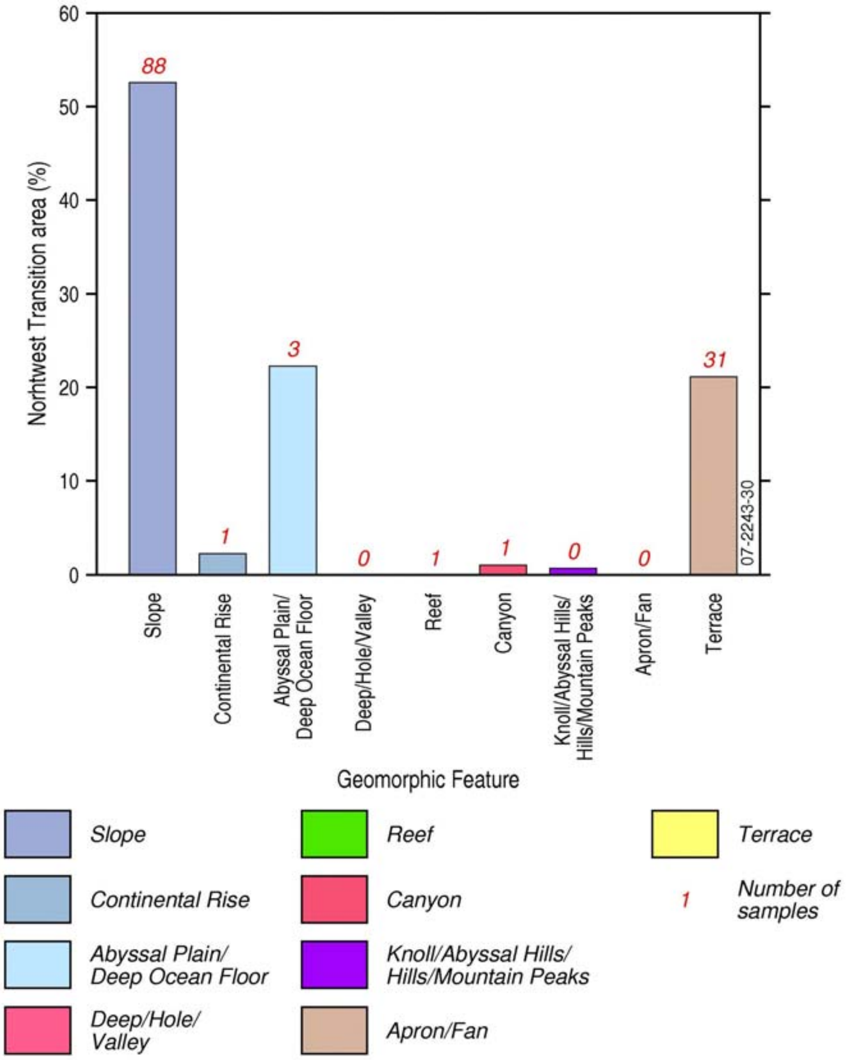
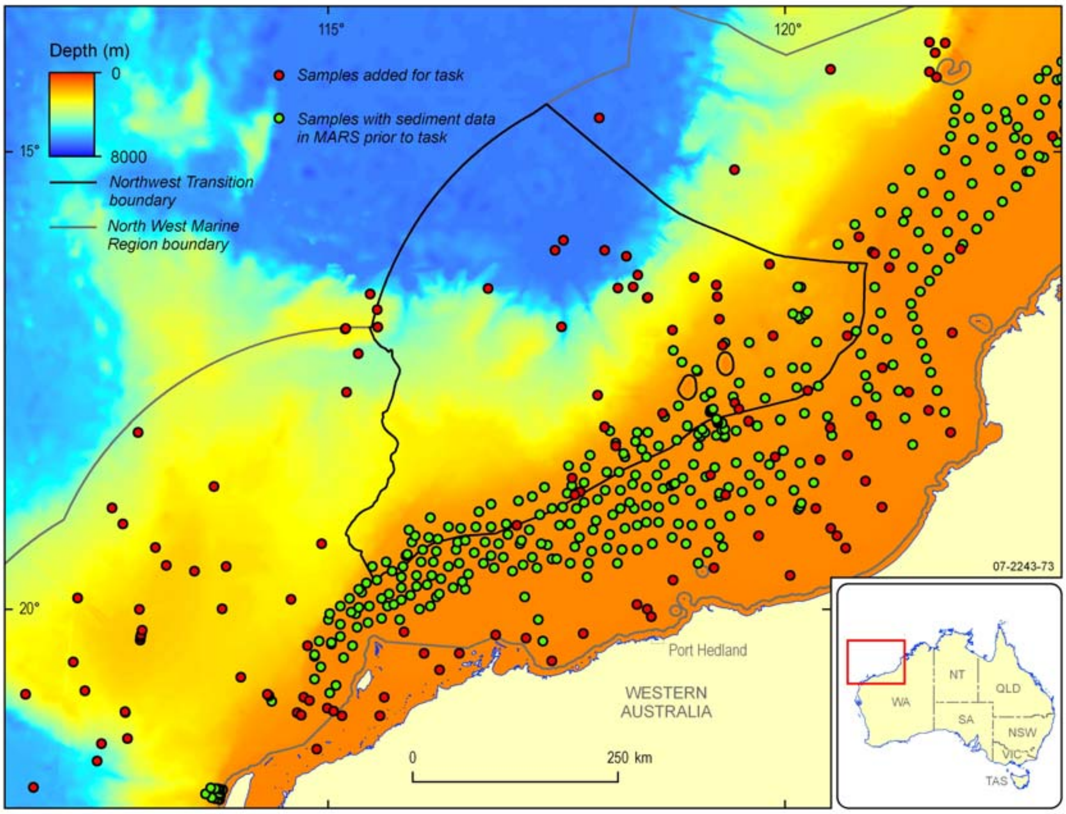


Figure 5.24. a) Geomorphology of the Northwest Transition (NWT) with location of sediment samples; and b) Percentage area of each geomorphic feature within the NWT with number of corresponding sediment samples.



a)

b)

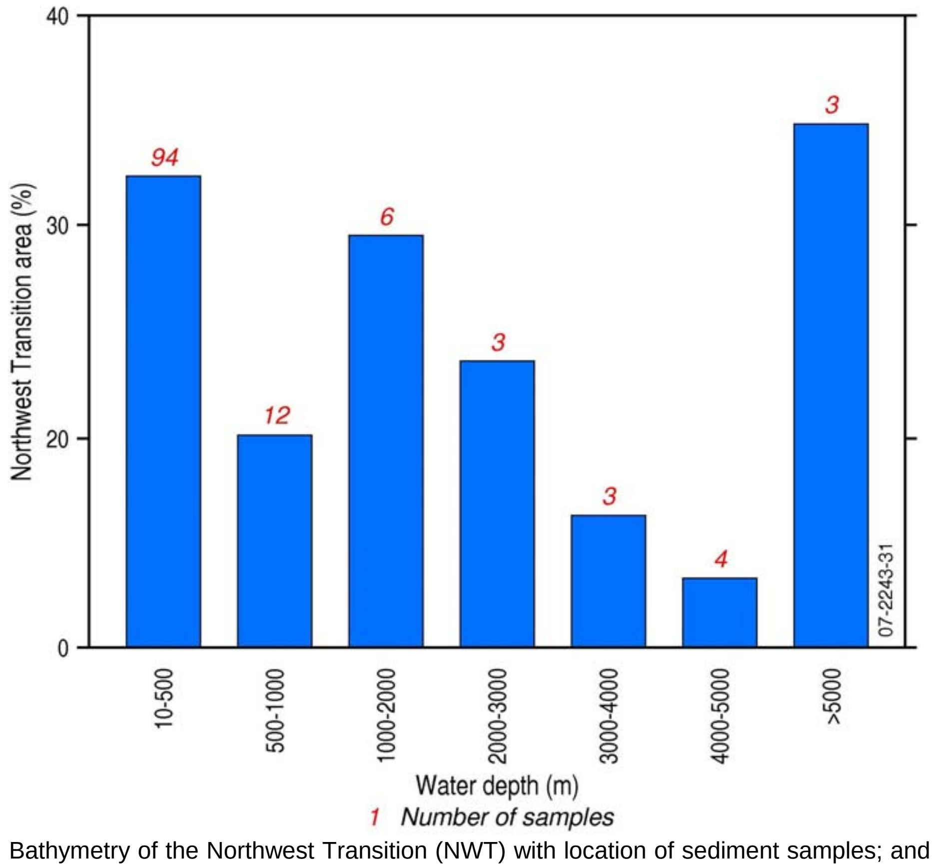


Figure 5.25. a) Bathymetry of the Northwest Transition (NWT) with location of sediment samples; and b) Percentage area of each bathymetry class within the NWT with number of corresponding sediment samples.

Table 5.12. Details of the geomorphology of the Northwest Transition.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Province			
Slope	75.78	21.48	3.47
Rise	2.07	23.97	3.72
AP/DOF	22.15	40.63	1.41
Geomorphic Feature			
Slope (unassigned)	52.50	31.03	7.01
Rise (unassigned)	2.07	23.97	3.97
AP/DOF* (unassigned)	22.15	41.18	1.65
Deep/hole/valley	0.25	0.49	0.27
Reef	0.07	6.21	0.28
Canyon	1.08	18.42	1.86
Knoll/abyssal hills/mountains/peak	0.75	68.62	1.16
Apron/fan	0.20	50.61	3.18
Terrace	20.93	16.92	6.63

Table 5.13. Distribution of water depths covered by the geomorphology in the Northwest Transition.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Slope	1 – 5,705	1,540
Rise	4,220 – 5,695	5,160
AP/DOF	4,575 – 5,975	5,680
Geomorphic Feature		
Slope (unassigned)	180 – 5,700	1,540
Rise (unassigned)	4,220 – 5,695	5,160
AP/DOF (unassigned)	4,575 – 5,975	5,680
Apron/fan	135 – 460	335
Canyon	2,830 – 5,705	2,875
Deep/hole/valley	3,160 – 4,930	4,050
Knoll/abyssal hills/mountains/peak	1,700 – 2,550	1,910
Reef	1 – 420	145
Terrace	205 – 4,025	1,370

5.7.3. Sedimentology of the Northwest Transition

The NWT contains 125 grain size and 121 carbonate assays. A total of 100 (80%) samples occur within 100 km of the shelf break (Fig. 5.24a). Sediments in this area show variable textural properties. Sand is the dominant fraction in all samples, ranging from 8 to 100% with 63 samples exceeding 50%. Mud ranges from <1 to 87% with 28 samples exceeding 50%. Gravel varies from <1 to 83% and comprises <1% of sediment in 54 (43%) sample. Gravel is the dominant fraction in three samples with contents ranging from 64 to 92%.

Samples are distributed more sparsely over the rest of the slope, rise and AP/DOF. Textural properties of samples from this area show patterns with water depth. Samples from the area adjacent to the Rowley Shoals contain 25 to 95% sand, 0 to 75% mud and <5% gravel. Samples on the middle to lower slope contain <40% sand, and frequently <20%. Samples on the AP/DOF contain >80% mud with the remainder of sediment composed of sand.

Carbonate content of sediments in the NWT is also associated with water depth. Bulk carbonate ranges from 3 to 99%, and attains >50% in 118 samples. Low <1 to 76% carbonate contents occur only on the AP/DOF and continental rise. Within 100 km of the shelf break, carbonate content exceeds 80% in 95% of samples. For middle lower slope areas carbonate ranges from 40 to 80%, except adjacent to the Rowley Shoals where it exceeds 80%.

Carbonate content of gravel and mud textural size fractions display similar patterns to bulk carbonate. Carbonate sand exceeds 80% in all samples where sand was present, including samples from all geomorphic provinces of the NWT.

5.7.4. Sedimentology of significant geomorphic features

5.7.4.1. Slope

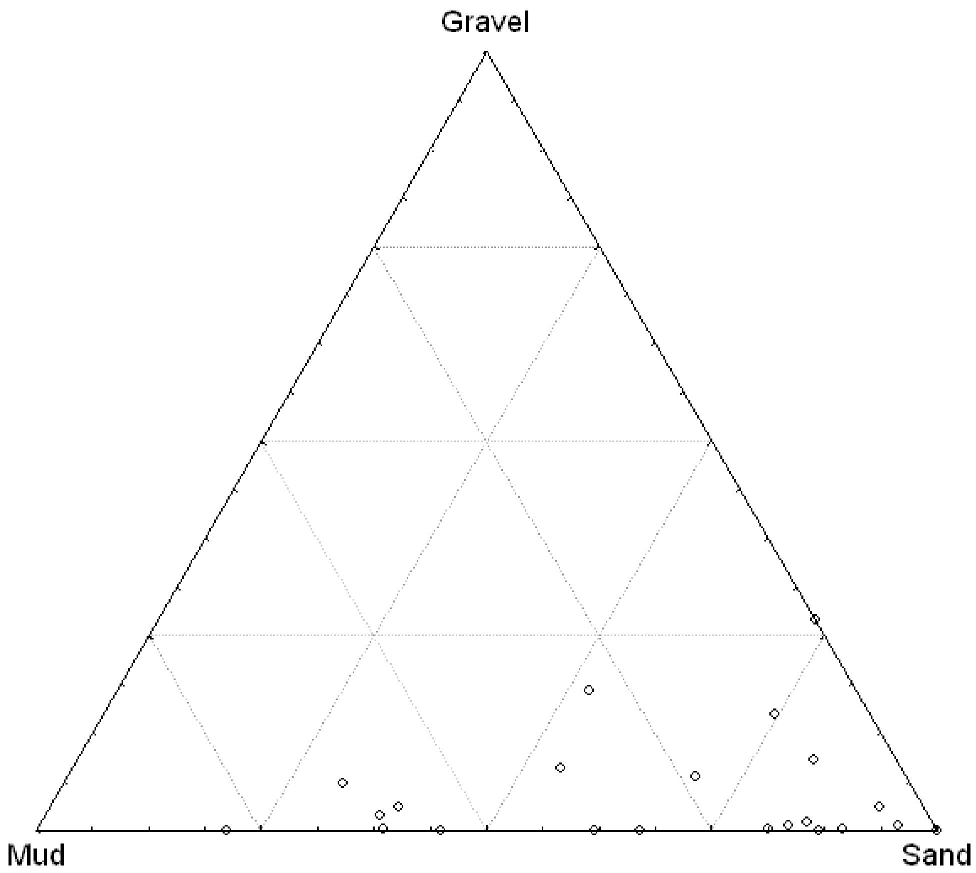
A total of 88 samples were obtained from the slope (Fig. 5.23b). Sand is the dominant fraction with contents generally ranging between 8 and 100% with 49 samples exceeding 50% (Fig. 5.26b). Mud is the next most abundant fraction and contents generally ranging between 1 and 88% and 34 samples containing >50% mud. Gravel concentrations generally range from 1 to 49%. However, gravel contents of up to 92% occur in three samples. Bulk carbonate content varies from 42 to 98%, with 84 samples exceeding 50% carbonate (Fig. 5.27b). Carbonate sand content ranges from 78 to 98% with 31 samples exceeding 90%. Carbonate mud content varies between 66 to 92% with three samples exceeding 90%. Carbonate gravel content ranges from 65 to 100% and attains 100% in 23 samples.

5.7.4.2. Argo Abyssal Plain

A total of three samples were obtained from abyssal plain/deep ocean floor environments. Despite the relatively large area of this province and widely spaced sample locations, variability in texture and composition of sediments is low. Mud is the dominant fraction, comprising >80% in all samples (Fig. 5.26 c). While sand comprises <20%, gravel was not present. Bulk carbonate content varies between 7 and 76%, although values <1% were observed at two locations. One sample contained >60% carbonate mud content. The small number of assays (3) for this feature means that these carbonate content percentages do not necessarily describe the entire distribution of textural and compositional characteristics of abyssal plains/deep ocean floor in the NWT.

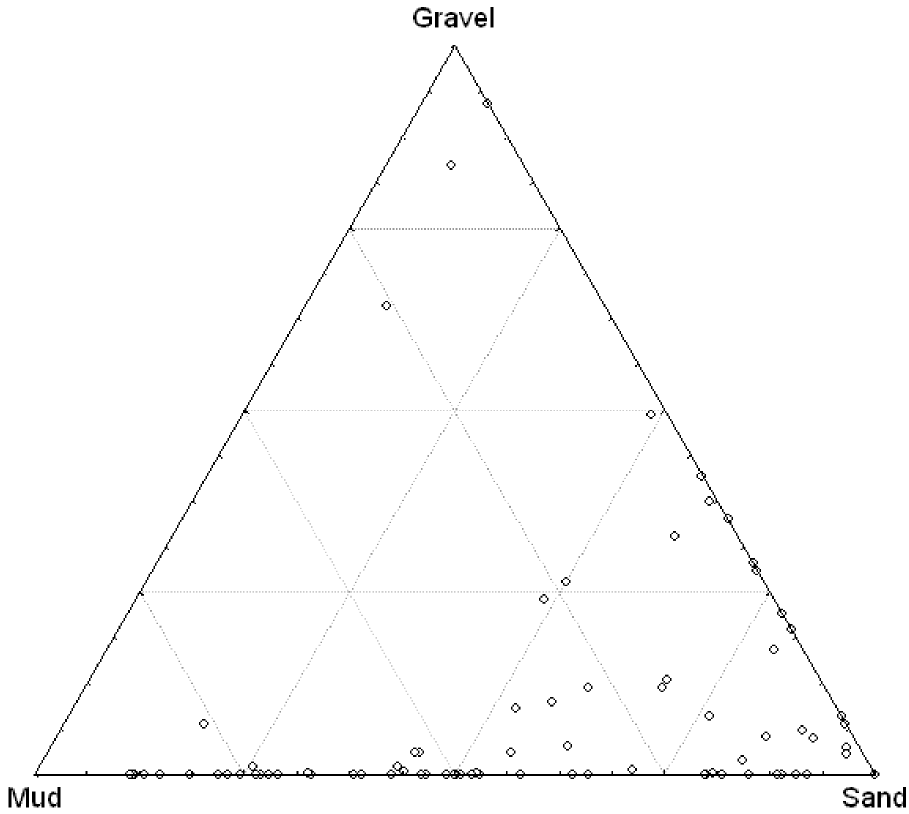
5.7.4.3. Upper Slope Terraces

A total of 22 samples were obtained from upper slope terraces. Sand is the dominant fraction with contents generally ranging from 21 to 100% and exceeding 50% in 16 samples (Fig. 5.26a). Mud is the next most abundant fraction with contents ranging from 4 to 79% with six samples containing >50% mud. Gravel content attains 27%. Sediments in adjacent slope areas show similar textural properties. Bulk carbonate content generally varies between 82 to 99% with 11 samples containing >90% (Fig. 5.27a). Carbonate sand content ranges from 91 to 97% with five samples exceeding 95%. Carbonate mud content varies between 76 and 84% and exceeds 80% in one sample. Carbonate gravel attains 100% in nine samples.



a)

b)



c)

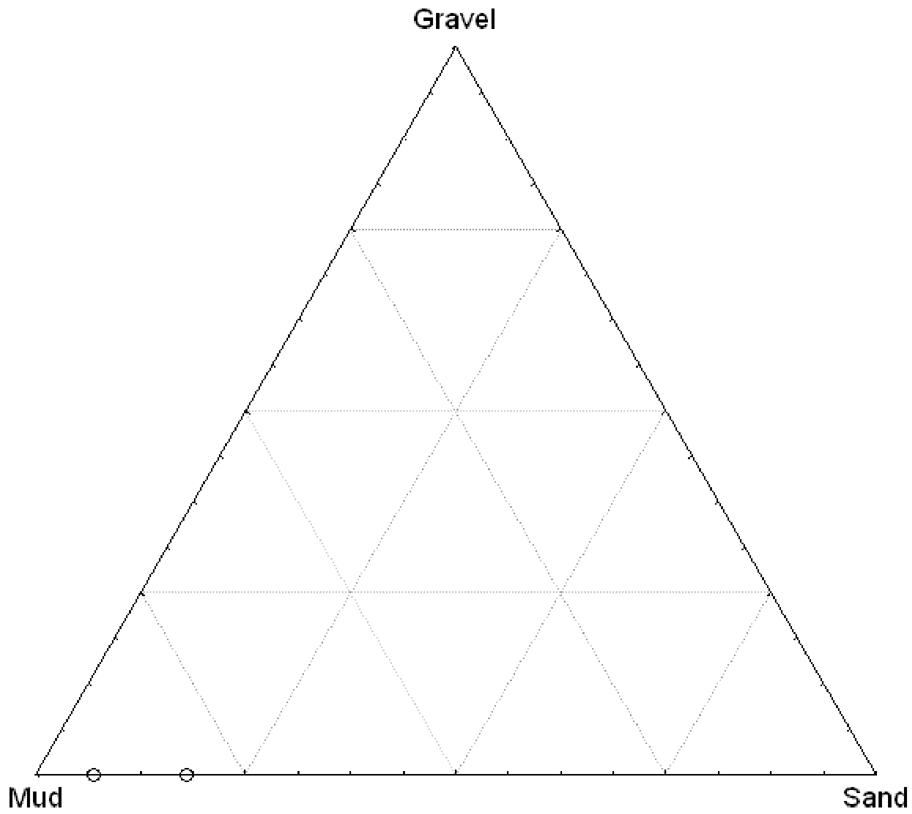
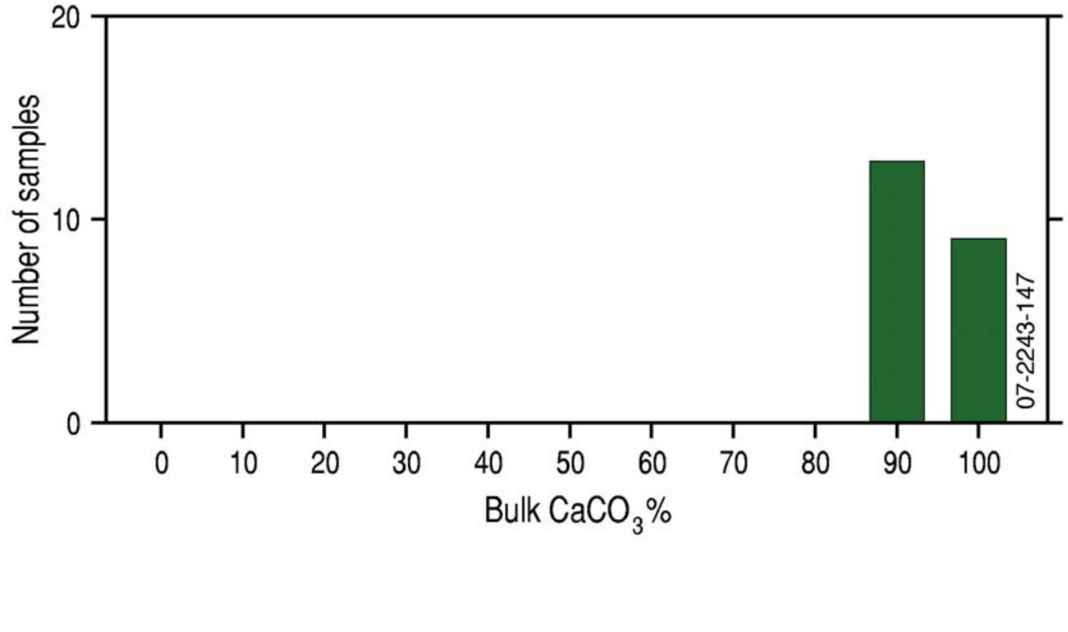


Figure 5.26. Textural composition (mud:sand:gravel ratio) of a) upper slope terrace and b) slope sediments c) Argo Abyssal Plain within the NWT.

a)



b)

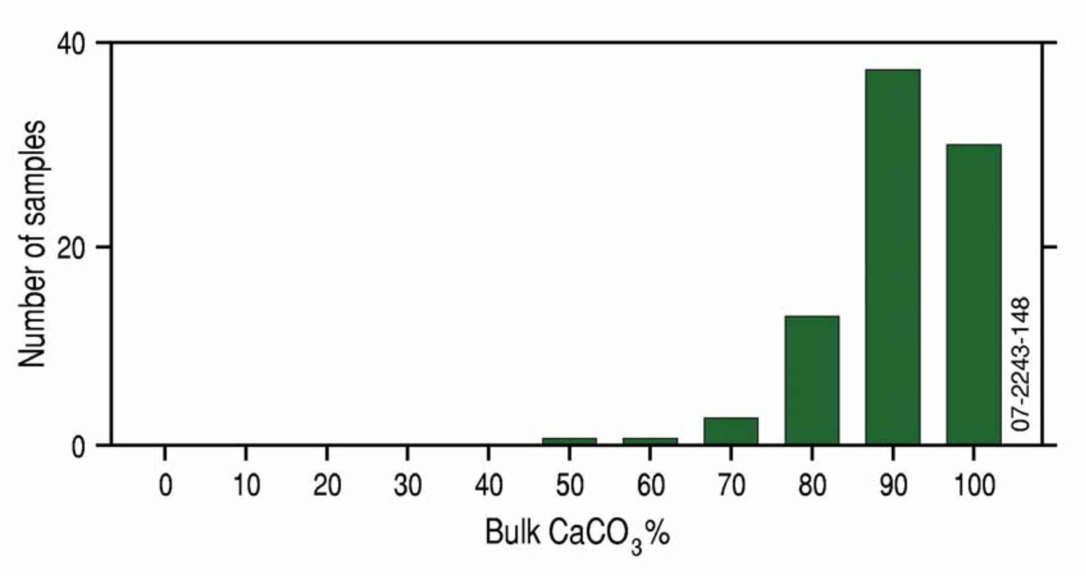


Figure 5.27. Carbonate content of a) terrace and b) slope sediments within the NWT.

5.8. NORTHWEST PROVINCE (NWP)

5.8.1. Geomorphology and bathymetry

The Northwest Province (NWP) covers a total area of 188,170 km², all of which is situated in the NWMR (Fig. 5.1). This bioregion represents 15% of the total area of the NWMR (Table 5.1) and approximately 2% of the total area of the EEZ. The NWP is located offshore of the western Australian margin between Exmouth and Port Hedland and is separated from the coast by the Northwest Shelf Province. It is bounded to the north by the NWT and to south by the Central Western Transition. This bioregion is composed entirely of slope environments, approximately 400 km from the shelf break to the outer EEZ boundary (Fig. 5.28a; Table 5.14). Water depths vary from 10 m locally near the shelf break to over 5,170 m on the lower slope, although almost 80% of the bioregion lies in depths between 1,000 and 3,000 m (Fig. 5.29b).

The slope contains seven types of geomorphic features. Features covering significant areas of the Northwest Province include: plateaus (49,310 km², 28% bioregion area), deeps/holes/valleys (33,150 km², 19%), terraces (14,530 km², 8%), trenches/troughs (10,120 km², 6%) and canyons (4,090 km², 2%). Ridges and knoll/abyssal hills/mountains/peaks each cover less than 1,500 km² (<1%) (Table 5.14). Geomorphic features could not be identified over 71,500 km² (38%) of the total area.

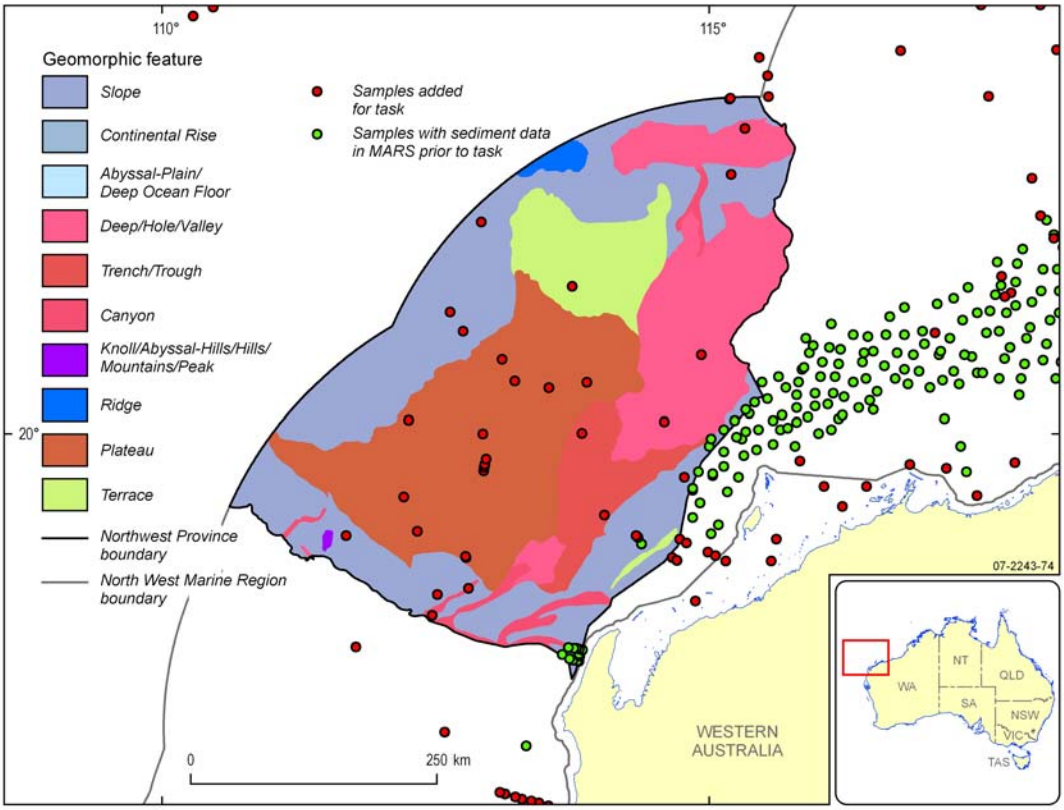
Four significant geomorphic features are identified for the NWP. Slope (unassigned) and deeps/holes/valleys cover significant areas of the bioregion (37 and 19% respectively). Trench/troughs in the NWP represent 100% of the area of this feature occurring in the NWMR. The Exmouth Plateau covers approximately 28% of the bioregion, and forms approximately 50% of the total area of plateaus in the NWMR. However, plateaus located in deep water have been shown to have relatively homogeneous sedimentology across the NWMR and therefore no information can be added by analysis at a bioregion scale.

5.8.2. Sample Coverage

The NWP is represented by 58 sample points (Figs. 5.28a). Approximately 32 (55%) samples occur on the upper slope within 80 km of the shelf break and in <1000 m water depth (Fig. 5.29a). A total of 12 samples occur clustered in a 15 km² area in the southeast corner of the bioregion around the heads of the Caperange Canyon. Other samples are distributed sparsely across the rest of the bioregion area, reaching an average sample density of 1:3,100 km².

Samples achieve adequate coverage to describe the sedimentology for all of the significant features. Slope (unassigned) contains 32 samples, resulting in an average density of 1:2,060 km². Plateaus contain 16 samples, resulting in an average density of 1:3,080 km². Deeps/holes/valleys and trenches/troughs contain three samples, resulting in an average density of 1:11,050 km² and 1:3,370 km², respectively. This study added 33 samples to the NWP, improving coverage of slope (unassigned) (8 samples added), plateaus (14), deeps/holes/valleys (3) and trenches/troughs (2).

a)



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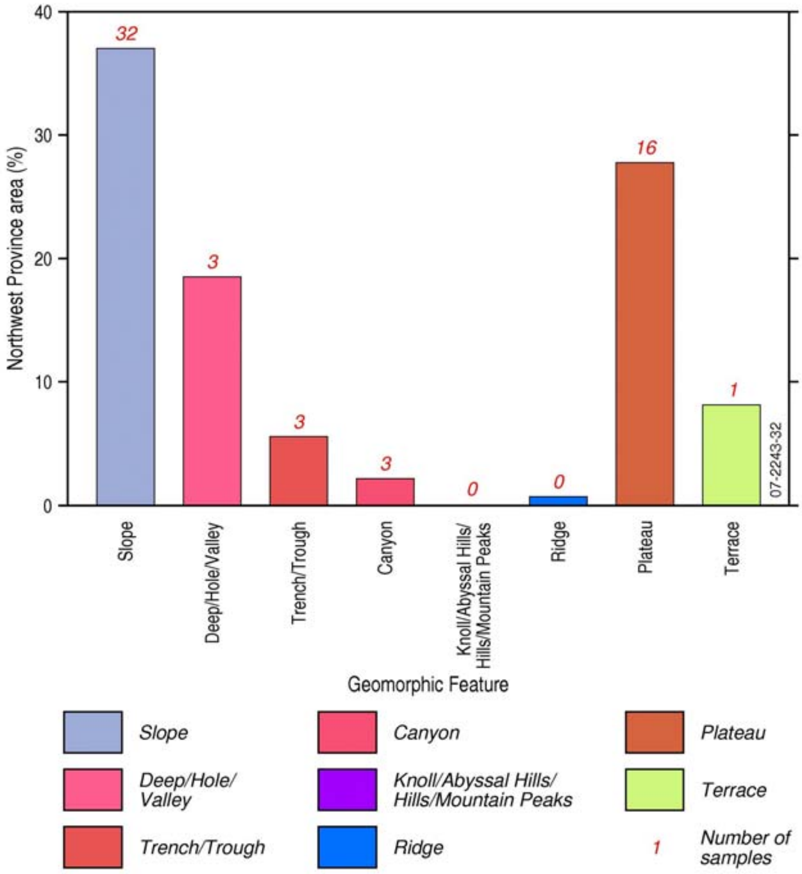
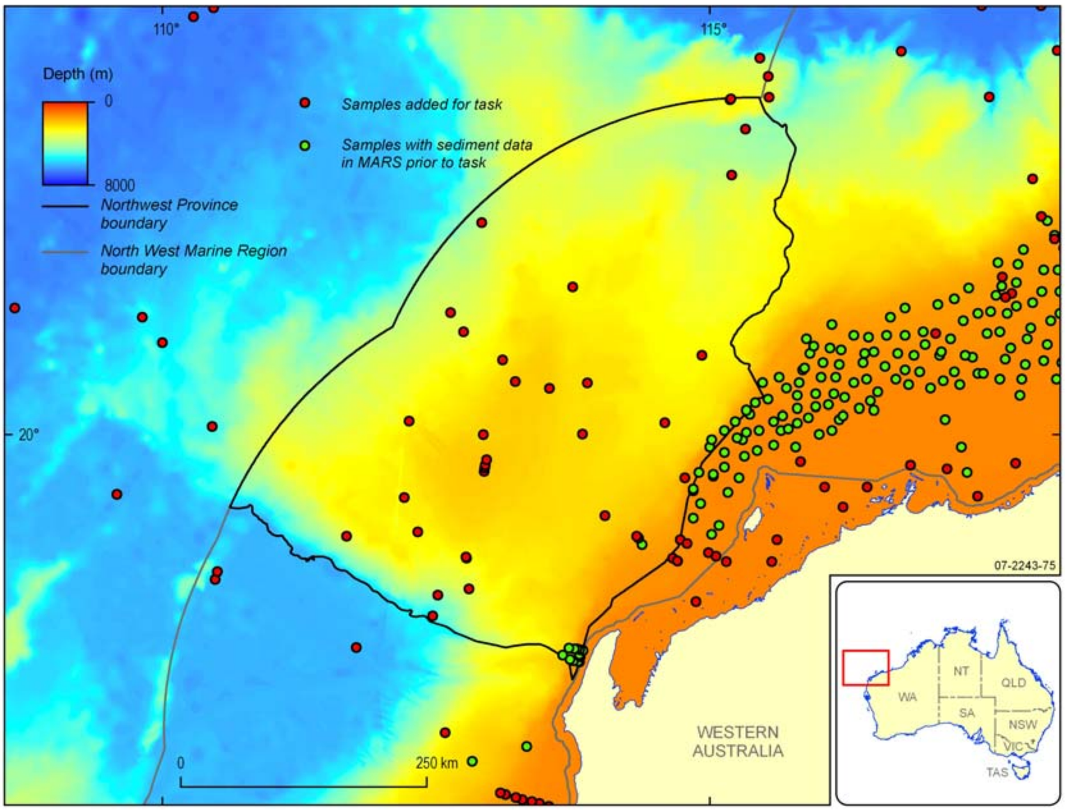


Figure 5.28. a) Geomorphology of the Northwest Province (NWP) with location of sediment samples; and b) Percentage area of each geomorphic feature within the NWP with number of corresponding sediment samples.



a)

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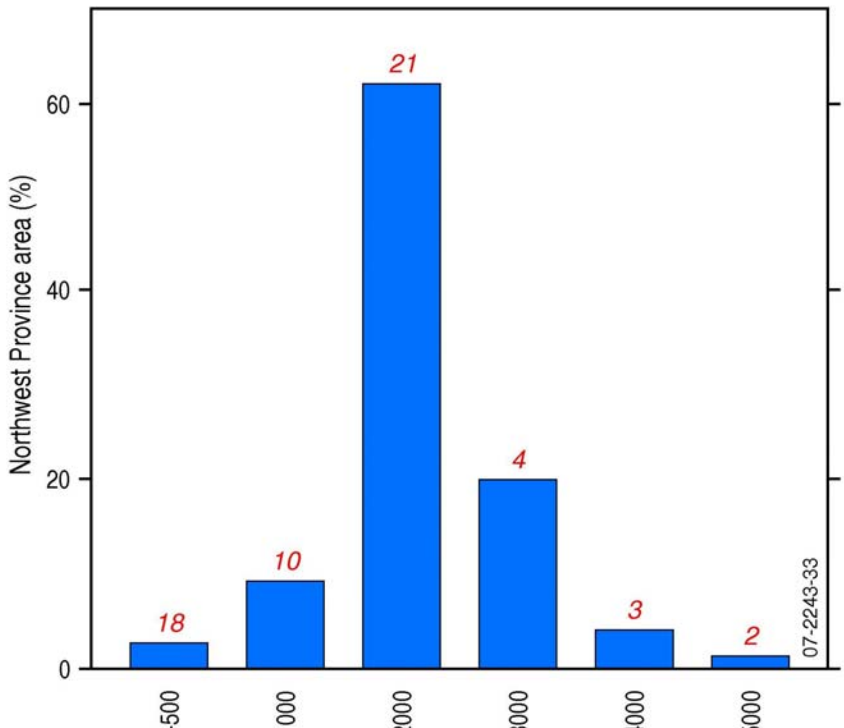


Figure 5.29. a) Bathymetry of the Northwest Province (NWP) with location of sediment samples; and b) Percentage area of each bathymetry class within the NWP with number of corresponding sediment samples.

Table 5.14. Details of the geomorphology of the Northwest Province.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Province			
Slope	100	27.58	4.46
Geomorphic Feature			
Slope (unassigned)	36.90	21.22	4.80
Deep/hole/valley	18.56	35.53	20.07
Trench/trough	5.67	100	5.82
Canyon	2.29	37.91	3.83
Knoll/abyssal hills/mountains/peak	0.09	8.45	0.14
Ridge	0.75	23.07	1.20
Plateau	27.61	52.40	3.30
Terrace	8.14	6.40	2.51

Table 5.15. Distribution of water depths covered by the geomorphology in the Northwest Province.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Slope	125 – 5,165	1,675
Geomorphic Feature		
Slope (unassigned)	125 – 5,165	5,045
Deep/hole/valley	535 – 5,045	4,510
Trench/trough	570 – 1,285	715
Canyon	200 – 4,815	4,615
Knoll/abyssal hills/mountains/peak	2,440 – 3,955	1,515
Ridge	1,665 – 2,085	420
Plateau	830 – 2,110	1,280
Terrace	290 – 2,060	1,770

5.8.3. Sedimentology of the Northwest Province

The NWP contains 58 grain size and 59 carbonate assays. Mud occurs in all but two sites with contents ranging from <1 to 97%. Mud contents for the area within 100 km of the shelf break have the highest variability (0 to 97%). Elsewhere in the bioregion, mud content consistently attains 50% with the remaining sample volume composed of sand (0 to 50%). Gravel comprises <1% in 53 (91%) samples. Gravel contents of >1% are only present in samples within 100 km of the shelf break, with contents exceeding 5% in two samples.

Carbonate content in the NWP exceeds 55% in all samples and exceeds 80% in 14 (24%) samples. Carbonate contents show some spatial zoning, but this does not correspond directly to changes in water depth. Within 100 km of the shelf break carbonate contents generally exceed

80% and range from 60 to 80% elsewhere in the bioregion. The exception to this trend occurs in the southern corner of the bioregion, near the shelf break in samples collected from submarine canyons. These comprise less carbonate than those for the rest of the bioregion with contents of <80% and mostly between 55 and 70%. Carbonate sand and gravel contents in this area generally exceed 75%. Carbonate mud contents are consistently <70%.

Across the NWP carbonate content generally ranges from 60 to 100% for the sand fraction and 60 to 80% for mud.

5.8.4. Sedimentology of significant geomorphic features

5.8.4.1. Slope

A total of 32 samples were obtained from slope features (Fig 5.30b). Mud is the dominant fraction, with contents ranging from 15 to 96% and 25 samples comprising >50% mud. Sand is the next most abundant fraction, with contents ranging from 4 to 85% and seven samples containing >50%. Sand concentrations are generally higher closer to the shelf break where samples show similar sedimentology to that observed in adjacent shelf features. Gravel concentrations generally range from <1 to 5% (Fig. 5.30b). Samples that contain gravel occur near the shelf break. Bulk carbonate content varies between 57 and 93% with 22 samples exceeding 70% (Fig. 5.31a). Carbonate sand varies from 75 to 95% with 10 samples containing >90%. Carbonate mud varies from 59 to 81% with eight samples exceeding 70%. Carbonate gravel ranges between 90 and 100% and attains 100% in seven samples.

5.8.4.2. Deep/hole/valleys

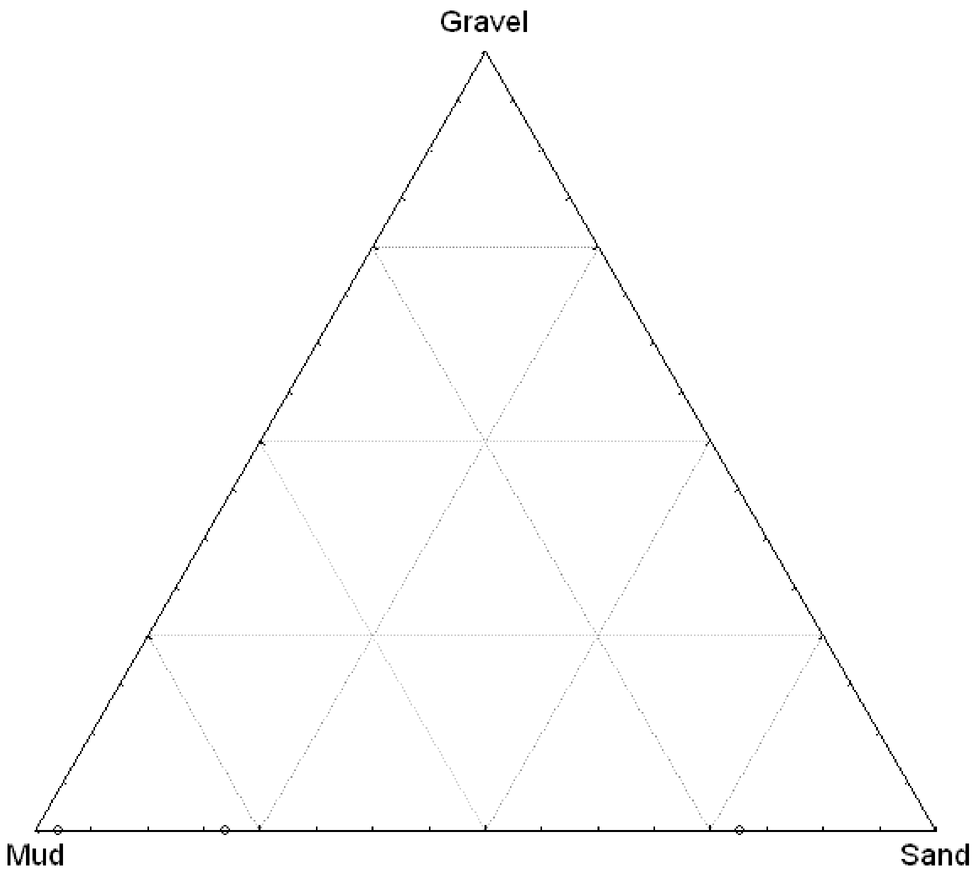
A total of three samples were obtained from deeps/holes/valleys (Fig. 5.30a). Sediments are principally composed of sand and mud, with contents ranging from 3 to 78% and 22 to 97%, respectively (Fig. 5.30a). Bulk carbonate content of sediments comprises between 68 and 85%, with high bulk carbonate contents often corresponding to increases in sand content. Samples occurring on the slope adjacent to deeps/holes/valleys generally show similar sedimentology to samples collected within these features. The small number of assays for this feature means that samples may not accurately characterise the range and distribution of sediments present in deeps/holes/valleys in the NWP.

5.8.4.3. Trench/troughs

A total of three samples were obtained from trenches/troughs (Fig. 5.30c). Mud is the dominant fraction, with contents generally ranging between 84 and 89% (Fig. 5.30c). Sand is the next most abundant sediment fraction, with contents ranging between 11 and 16%. Gravel is not present. Bulk carbonate content of sediments comprises between 60 and 70% (Fig. 5.31b). Samples collected from plateaus and deeps/holes/valleys occurring adjacent to ridges in the NWP show similar sedimentology to those collected within ridges. The small number of assays for this feature means that samples may not accurately characterise the range and distribution of sediments present in trench/troughs in the NWP.

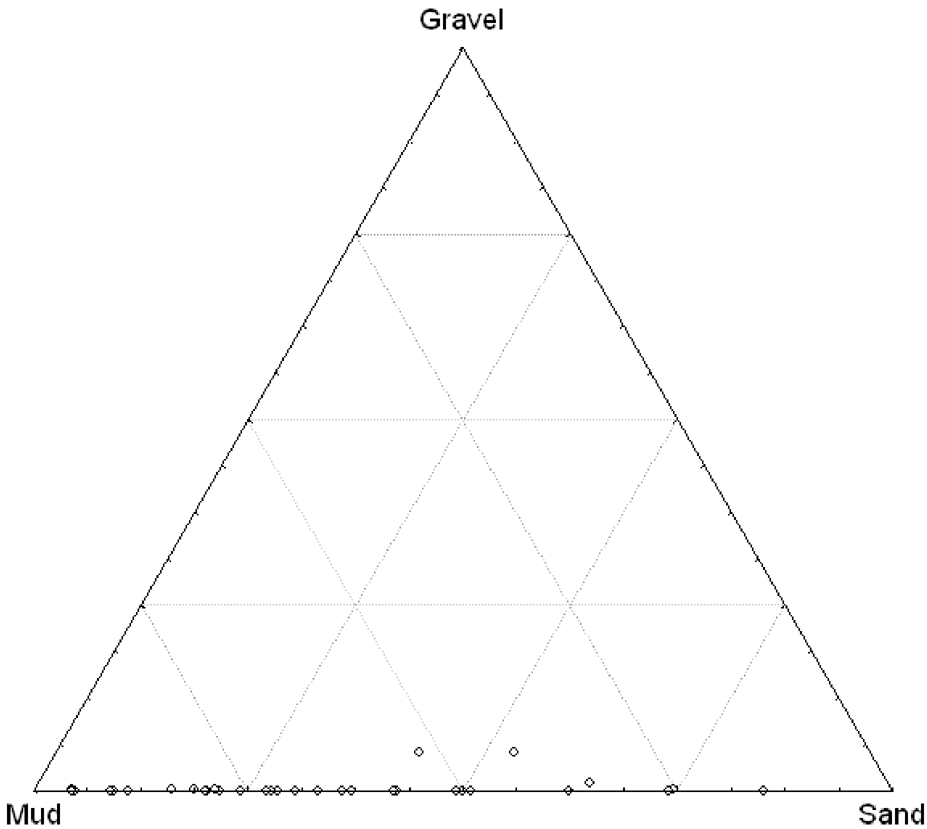
5.8.4.4. Deep water plateaus

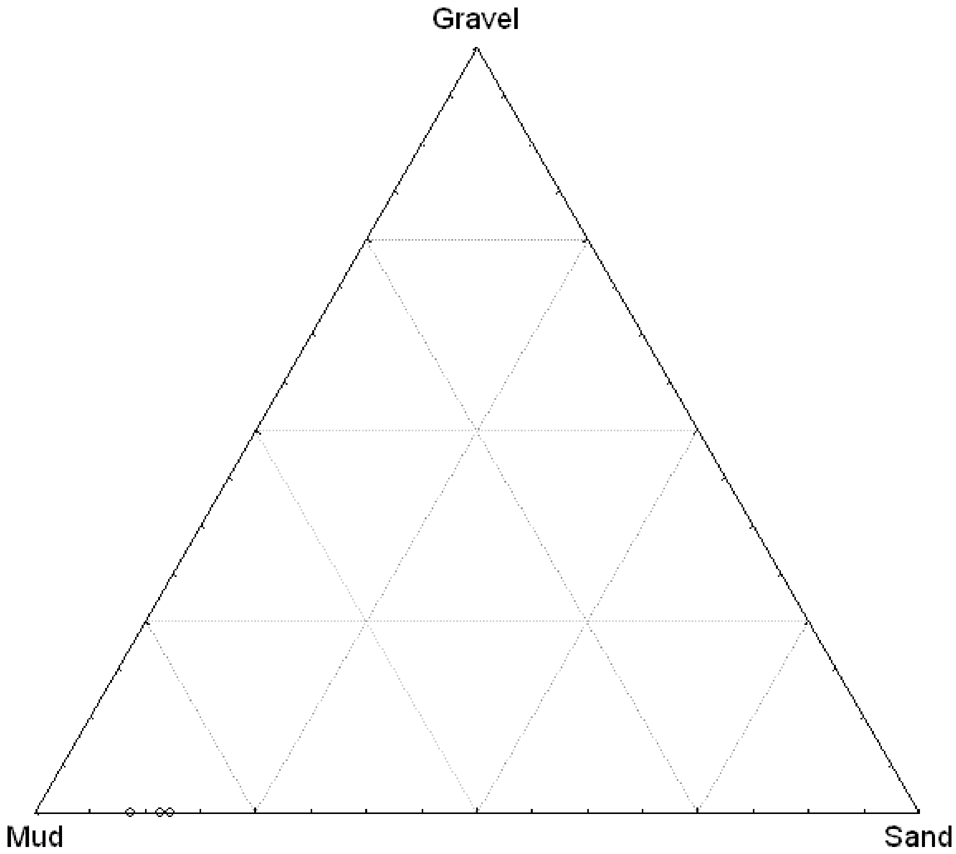
A total of 16 samples were obtained from deep water plateaus (>500m) (Fig. 5.30d). Mud is the dominant fraction, with contents varying from 51 to 83% (Fig. 5.30c). Sand is the next most abundant sediment fraction, with contents ranging between 17 and 48%. Gravel is not present. Bulk carbonate content of sediments comprises between 68 and 82% (Fig. 5.31c). Carbonate mud ranges between 68 and 87%, with 10 samples attaining >70%. Carbonate sand content varies from 92 to 99%.



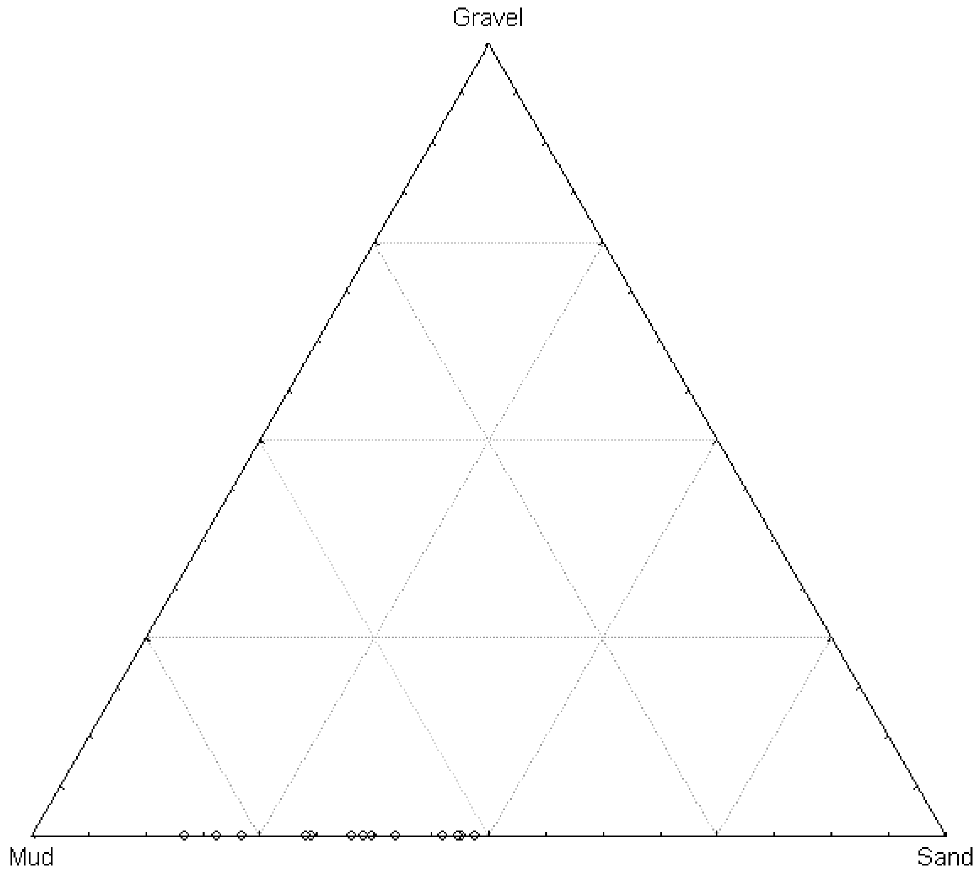
a)

b)





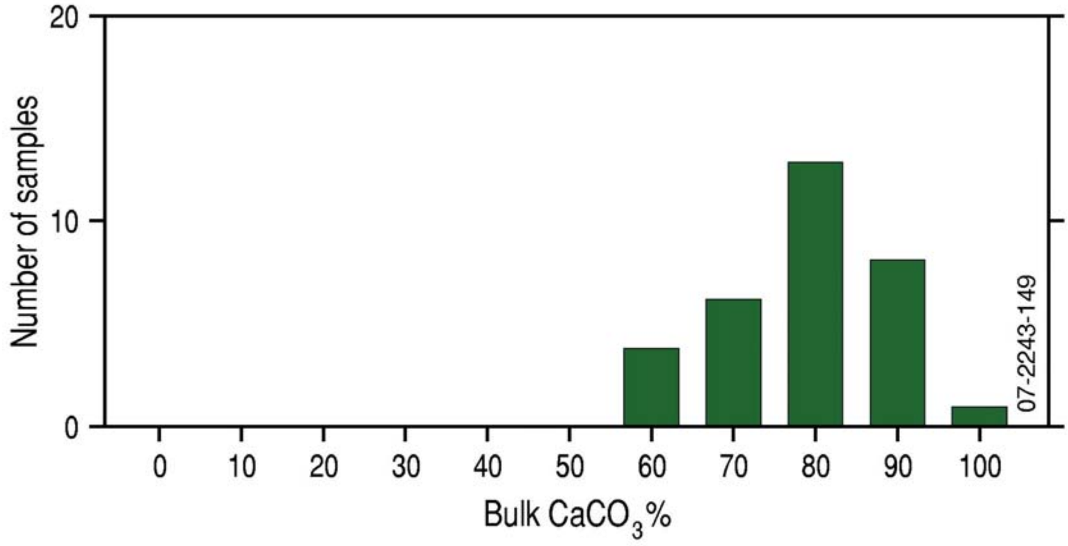
c)



d)

Figure 5.30. Textural composition (mud:sand:gravel ratio) of a) deep/hole/valley; and b) slope c)Trench/troughs d)Deep water plateaus sediments within the NWP.

a)



20
10
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Number of samples
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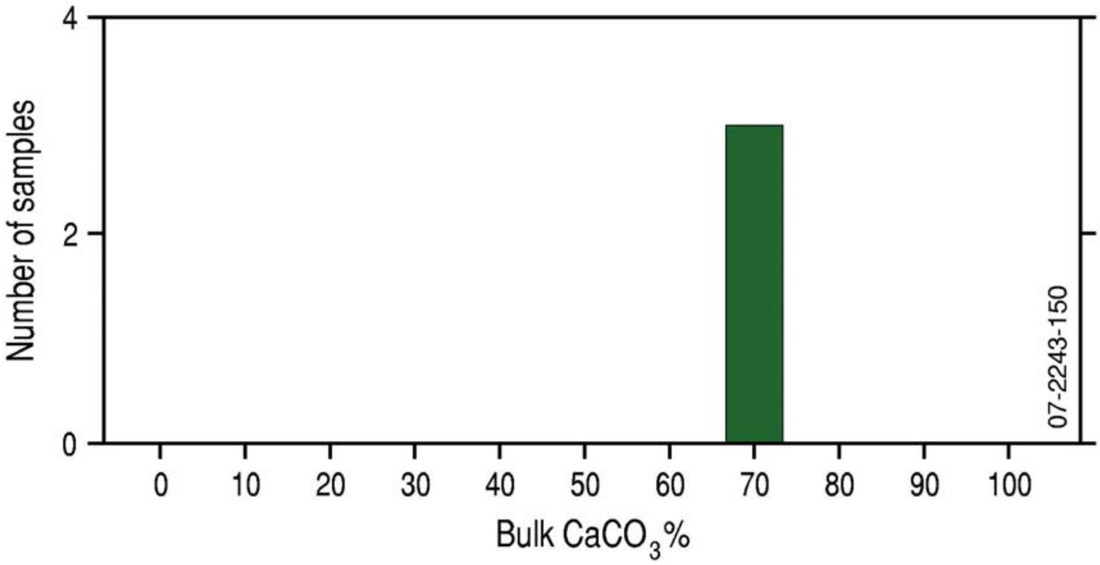

4
2
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Number of samples
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80
90
100
Bulk $CaCO_3$%
07-2243-150

c)

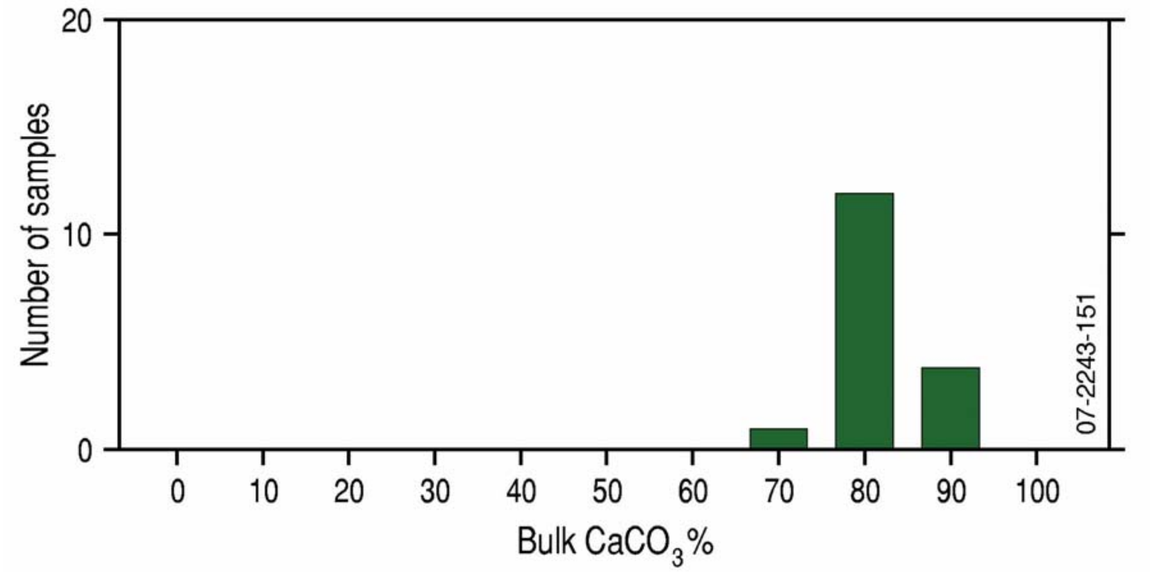


Figure 5.31. Carbonate content of a) slope b)Trench/troughs and c)Deep water plateaus sediments within the NWP.

5.9. CENTRAL WESTERN TRANSITION (CWT)

5.9.1. Geomorphology and bathymetry

The Central Western Transition (CWT) covers a total area of 162,890 km², all of which is situated in the NWMR (Fig. 5.1). This bioregion represents 15% of the total area of the NWMR. The CWT is located off the shelf between Dirk Hartog Island and Northwest Cape and is separated from the coast by the Central Western Shelf Province in the south and the Central Western Shelf Transition in the north. It lies on the southern boundary of the NWMR and is bounded to the north by the NWP and to south by the CWP (partially included in the NWMR).

More than 51,930 km² 30%) of the CWT is located on the slope (Fig. 5.32b; Table 5.16). Smaller areas in the northwest of the region are located on the Cuvier Abyssal Plain (40,080 km², 25%) and adjacent rise (7,520 km², 5%). The bioregion's eastern boundary coincides with the shelf break and comes within a few kilometres of the coast in the north near Northwest Cape. Water depths in the bioregion range from 10 m near the shelf break to approximately 5,330 m on the Cuvier Abyssal Plain (Fig. 5.33a). The bioregion contains a relatively large percentage of deep water areas relative to other bioregions in the NWMR. Approximately 69,700 km² (40%) of the CWT occurs in water depths >4000 m, and <35,000 km² (20%) of the bioregion occurs in water shallower than 1,000 m (Fig. 5.33b).

The CWT contains large areas of slope (unassigned) (51,930 km², 32% CWT area) and abyssal plain/deep ocean floor (40,080 km², 25%), terraces (36,610 km², 22%), deeps/holes/valleys (12,180 km², 7%), saddles (7,880 km², 5%) and rise (7,520 km², 5%). Plateaus, canyons, ridges and knoll/abyssal hills each cover less than 2,500 km² or 1.5% of the bioregion (Table 5.16).

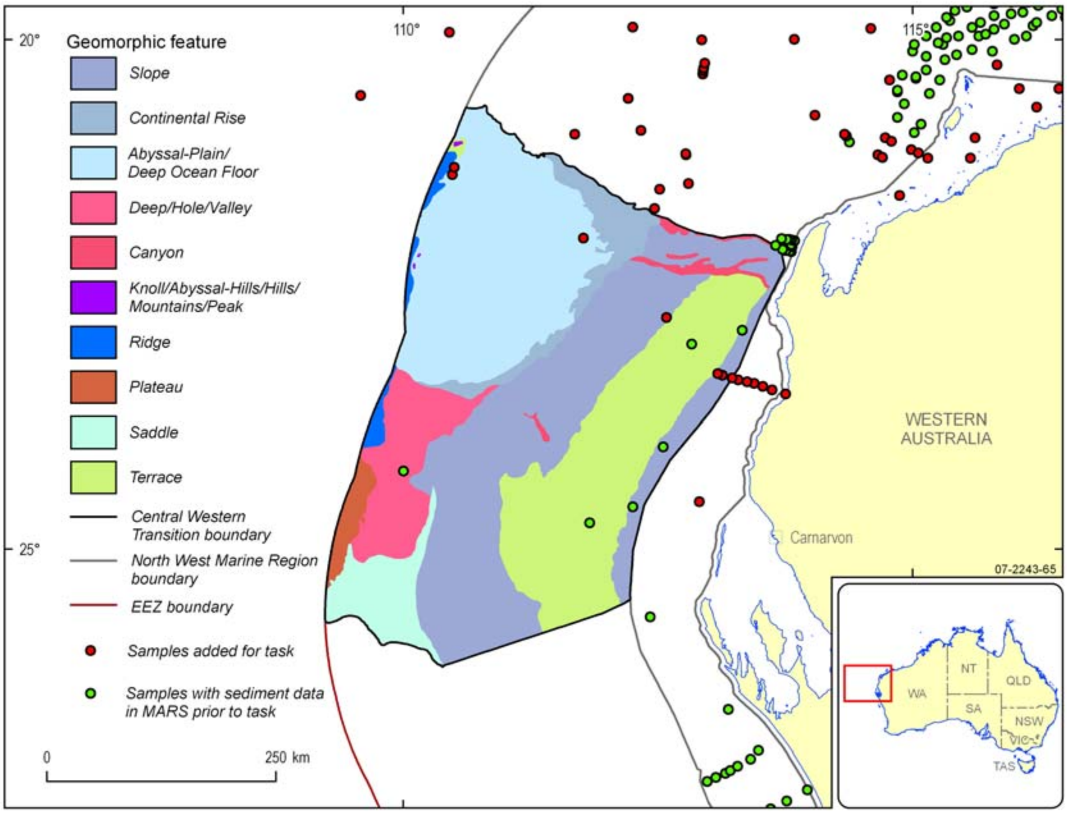
Four significant geomorphic features are identified for the CWT. Slope (unassigned) forms a significant area of the CWT. The CWT contains the entire area of the Cuvier Abyssal Plain included in the NWMR. This forms >40% of the total area of AP/DOF in the NWMR. This feature has a geological history and morphology that differs from areas of abyssal plain elsewhere in the NWMR (Chapter 3). More than 65% of the Canarvon Terrace occurs within the CWT (the remained of this terrace occurs outside the NWMR) and has a morphology and tectonic history that differentiates it from other terraces in the NWMR. The CWT also contains almost the entire area of saddles in the NWMR.

5.9.2. Sample Coverage

The CWT is represented by 15 samples (Figs. 5.32a). Approximately 50% of these occur on the upper slope near the shelf break in <500 m water depth (Fig. 5.33a). More than 35% of samples occur in water depths of >4,000 m (Fig 5.33b). These samples provide the majority of sediment information for areas at these water depths within the NWMR. Average sample density across the bioregion is 1:10,850 km².

Samples achieve adequate coverage to describe the sedimentology in two of the four significant features identified for the CWT. Slope (unassigned) contains six samples, resulting in an average sample density of 1:8,660 km². A total of four samples were collected from the Cuvier Abyssal Plain, resulting in an average density of 1:10,020 km².

Despite targeted sample addition, not enough samples were collected from the Carnarvon Terraces or saddles to describe sedimentology for these features. Six samples were added to the CWT for this study. These increased sample coverage on the slope (unassigned) (3 samples added), abyssal plain/deep ocean floor (2) and knoll/abyssal-hill/hills/mountains/peak (1). No additional samples collected from the Carnarvon Terrace or saddles were available for procurement.



a)

b)

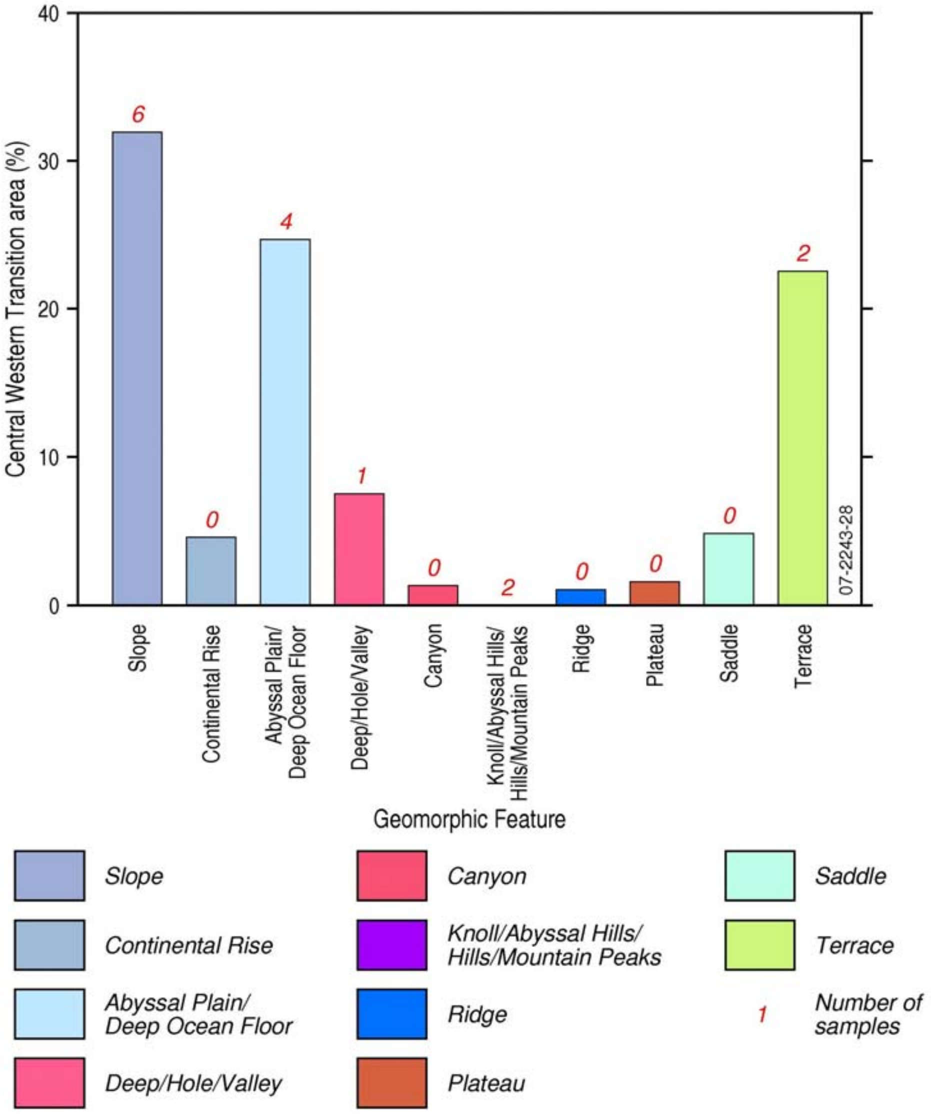
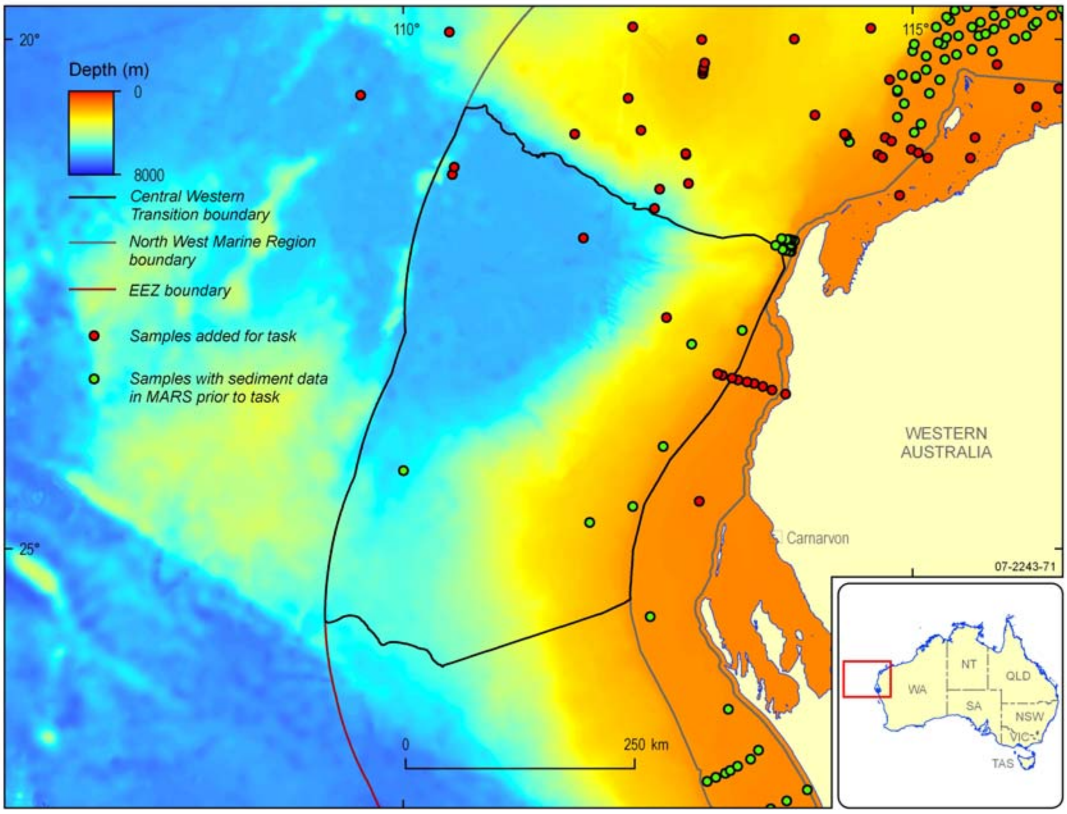


Figure 5.32. a) Geomorphology of the Central Western Transition (CWT) with location of sediment samples; and b) Percentage area of each geomorphic feature within the CWT with number of corresponding sediment samples.

a)



b)

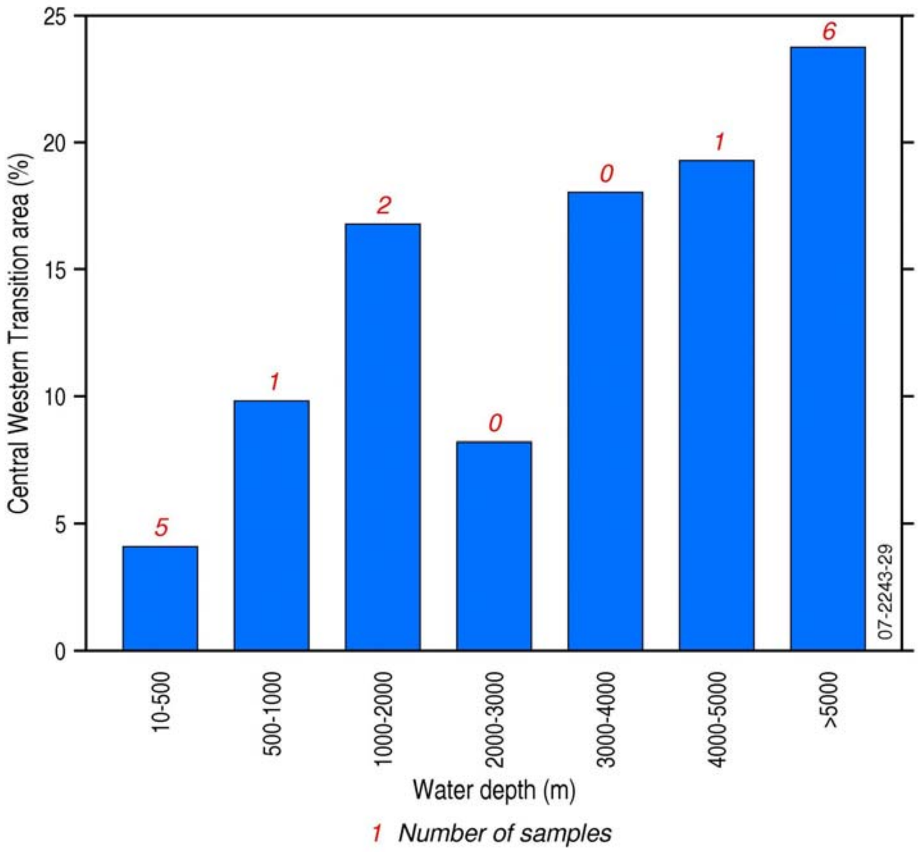


Figure 5.33. a) Bathymetry of the Central Western Transition (CWT) with location of sediment samples; and b) Percentage area of each bathymetry class within the CWT with number of corresponding sediment samples.

Table 5.16. Details of the geomorphology of the Central Western Transition.

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion
Geomorphic Province			
Slope	69.95	17.59	2.84
Rise	4.62	47.47	7.36
AP/DOF*	25.43	41.40	1.44
Geomorphic Feature			
Slope (unassigned)	31.88	16.72	3.78
Rise (unassigned)	4.62	47.47	7.85
AP/DOF* (unassigned)	24.60	40.60	1.63
Deep/hole/valley	7.48	13.06	7.38
Canyon	1.33	20.09	2.03
Knoll/abyssal hills/mountains/peak	0.07	5.35	0.09
Ridge	1.15	32.43	1.69
Plateau	1.56	2.69	0.17
Saddle	4.84	98.67	5.38
Terrace	22.47	16.13	6.32

Table 5.17. Distribution of water depths covered by the geomorphology in the Central Western Transition.

Feature	Depth Range (m)	Mean Depth (m)
Geomorphic Province		
Slope	110 – 5,335	5,220
Rise	4,155 – 5,300	1,150
AP/DOF	3,290 – 5,455	2,165
Geomorphic Feature		
Slope (unassigned)	110 – 5,335	5,220
Rise (unassigned)	4,155 – 5,300	1,150
AP/DOF (unassigned)	3,375 – 5,455	2,080
Deep/hole/valley	3,805 – 5,270	1,470
Canyon	215 – 4,980	4,765
Knoll/abyssal hills/mountains/peak	4,490 – 5,085	595
Ridge	3,290 – 5,180	1,895
Plateau	3,370 – 4,625	1,255
Saddle	3,655 – 4,300	650
Terrace	260 – 4,995	4,735

5.9.3. Sedimentology of the Central Western Transition

A total of 15 grain size and carbonate assays occur in the CWT. Sand content ranges from <1 to 97%, gravel content from 0 to 7%, and mud content from <1 to 100%. Mud and sand comprise the majority of the sediment. Gravel comprises <1% in 13 (87%) samples and is absent in 9 (60%). Mud comprises <5% in four (27%) samples and exceeded 95% in five (33%) samples.

Sediment grain size decreases with increasing water depth. Samples within 100 km of the shelf break contain >50% sand with <1% mud and <20% gravel. Samples elsewhere on the slope generally contain sand and mud in ratios varying between 40:60 and 60:40, with gravel not exceeding 1%. Sediments in this area of the CWT are coarse-grained compared with those at similar water depths elsewhere in the NWMR. Samples that occur on the AP/DOF contain >95% mud.

Carbonate content exceeds 75% at all locations except for four, where carbonate ranges from 37 to 73%. Samples with carbonate contents of <80% occur on the slope in the north of the bioregion and on the AP/DOF. Carbonate sand and gravel are consistently >80%. Where analysed, the carbonate content of mud ranges from 40 to 85%.

5.9.4. Sedimentology of significant geomorphic features

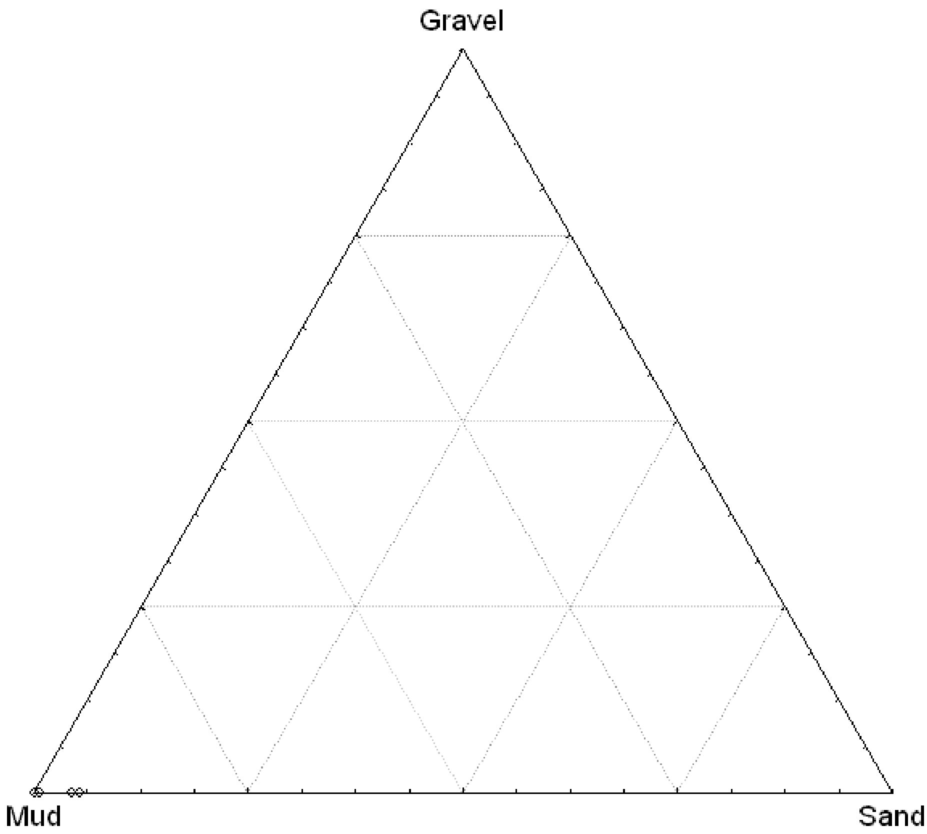
5.9.4.1. Slope

A total of six samples were obtained from the slope. Sand is the dominant fraction ranging between 47 and 97% (Fig. 5.34b) and exceeding 80% in four samples. Mud is the next most abundant fraction, with contents generally <30% although mud exceeding 52% in one sample (Fig. 5.35). Gravel content is <7% for all samples. Bulk carbonate content ranges between 76 and 91% and exceeds 90% in two samples (Fig. 5.35). Carbonate sand varies from 90 to 94% in five samples. Carbonate gravel ranges from 95 to 100% and attains 100% in three samples.

5.9.4.2. Cuvier Abyssal Plain

A total of four samples were obtained from the Cuvier Abyssal Plain. Mud is the dominant fraction, with contents ranging from 95 to 100% (Fig. 5.34a). Sand forms the remainder of sediment volume. Bulk carbonate content is bimodal, with a total of approximately 50% of sediments containing either between 30 and 50% or 70 and 80%.

a)



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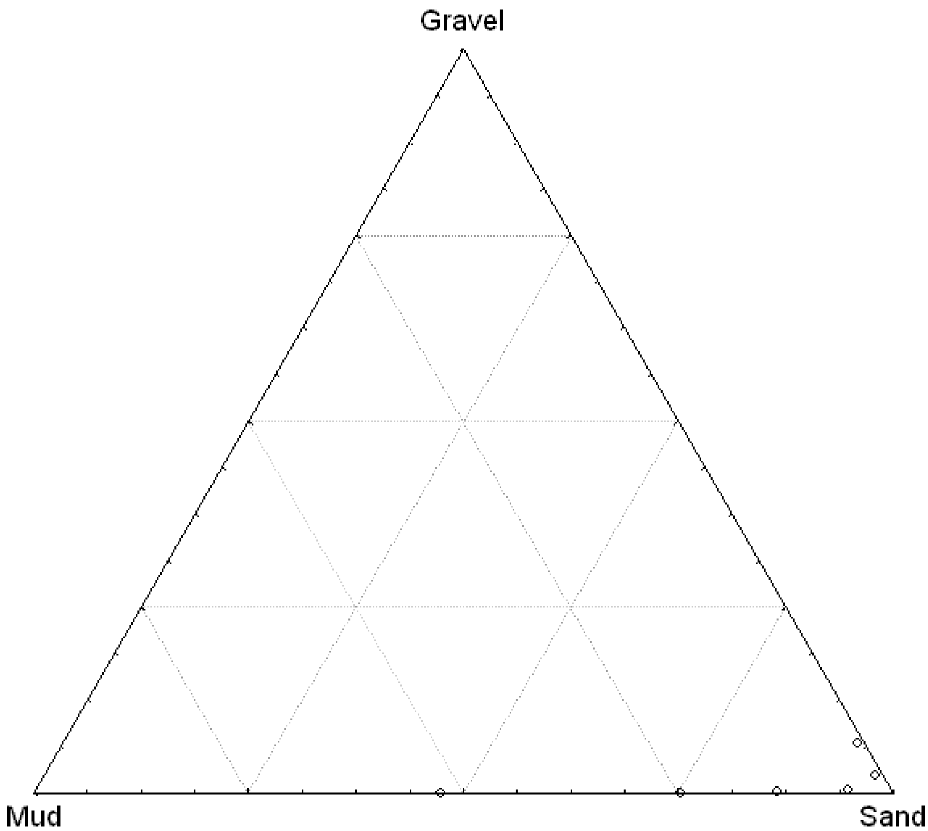

Figure 5.34. Textural composition (mud:sand:gravel ratio) of a) abyssal plain/deep ocean floor; and b) slope sediments within the CWT.

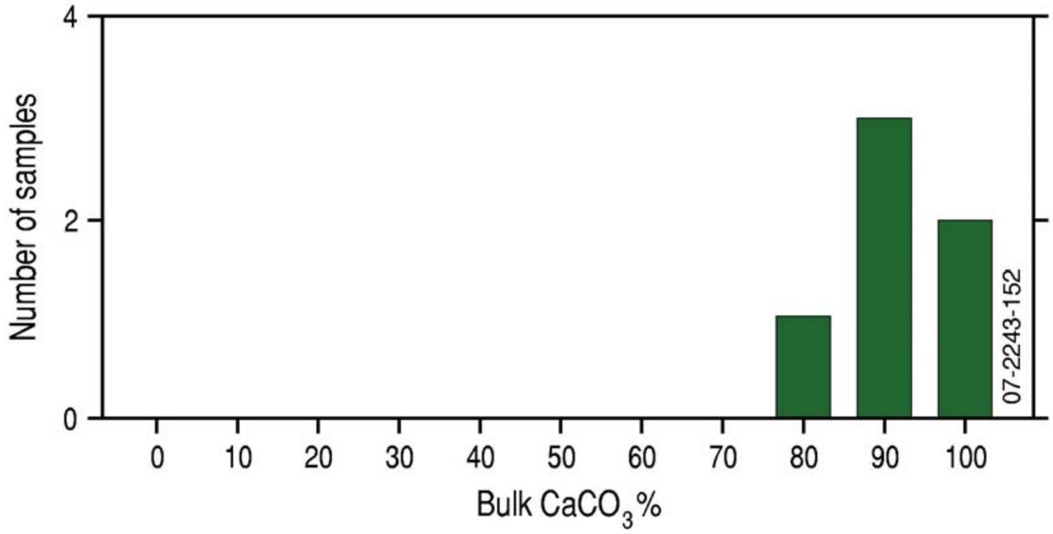

Figure 5.35. Carbonate content of slope sediments within the CWT.

6. Summary and Discussion

Textural and compositional data generated during this study for the NWMR and NNMR permits a quantitative comparison of sedimentology for Australia's Northwest and Northern Margin. The data builds on previous predominantly qualitative studies that currently exist for the region. Previous work for the area has focussed principally on the shelf, and consequently the following discussion is largely restricted to a comparison of our findings with the results of previous sediment models for the shelf. The implications of seabed sediment distribution for marine habitat mapping are also discussed.

6.1. SEDIMENT TRENDS OF THE NWMR

New consistent quantitative data for the NWMR have revealed regional scale patterns in sediment distribution not apparent in previous studies and forms a framework within which local scale patterns can be understood in a regional context. New data reveal some of the seabed complexity. At a regional scale our data show that seabed sediments become finer with increasing water depth in a margin parallel pattern. Variation in sediment texture and composition generally decreases with increasing water depth, with sediments on the rise and abyssal plain/deep ocean floor being relatively homogeneous compared to those on the slope and shelf. The fining and homogenisation of sediment texture with distance offshore is predominantly the result of decreasing energy levels and sediment transport mechanisms (for a detailed explanation see Section 3).

The shelf is predominantly composed of sand, and the abyssal plain/deep ocean floor is composed of mud. Areas of gravel occur mostly on the inner, middle and outer shelf/slope and are generally absent from the abyssal plain/deep ocean floor. This broad zoning and fining of sediment type with water depth has also been observed in similar reports by Geoscience Australia, notably on the South-West Australian margin (Potter et al, 2006). Calcium carbonate concentrations are highest on the inner, middle and outer shelf, and represent either relict or recent carbonate deposits. The high concentration of carbonate within this region has also been observed by Carrigy and Fairbridge (1954), Colwell and von Stakelberg (1981), Dix (1989), Dix et al. (2005), James et al. (2004), Jones (1970, 1973), and van Andel and Veevers (1967).

At a local scale our results agree with previous sedimentological work on the inner, middle and outer shelves and slope. Our data indicate distinct changes in sediment characteristics to the north of the Leveque Rise where high mud concentrations and low sand concentrations occur, similar to that noted in previous studies (van der Kaars, 2003; Carrigy and Fairbridge, 1954; Jones, 1971; Jones, 1973). New data have allowed us to more accurately map the extent and recognise the regional significance of this change.

High resolution data generated by Geoscience Australia for the seabed in the EEZ have indicated that geomorphic features are characterised by a combination of several environments with zones of transition between these. For some geomorphic features, the new data allow us to more accurately predict and distinguish between the range of environments present and, where data are adequate, estimate the relative proportions of these. Distinct sedimentary environments occur in some geomorphic features and these including: abyssal plain/deep ocean floor, ridges, terraces, slope, deeps/holes/valleys, and banks/shoals. Establishing relationships between substrate type and geomorphic feature will assist in creating a more accurate prediction of the sedimentary environment in regions with sparse sample coverage.

6.1.1. Inner Shelf

Seabed sediments of the inner shelf are sand dominated, with localised accumulations of gravel and a large carbonate component (40-100%). Bulk carbonate content increases with sand content and sand content decreases with water depth. Our data and indicate that localised deposits of mud and gravel occur in the vicinity of the Dampier Archipelago, Port Hedland, Broome and to the north of the Leveque Rise. To the north of the Leveque Rise, inner shelf sediments are dominated by higher proportions of mud (20-40%) and gravel (40-80%) and lower proportions of sand (20-40%) and carbonate (20-40%). This pattern corresponds to the sedimentology of the region as observed by Carrigy and Fairbridge (1954). We also detected additional comparable areas of gravel (~40-80%) present locally on the inner shelf of the Bonaparte Gulf. Dix (1989) and Dix et al. (2005) observed that seabed sediments on the inner Dirk Hartog Shelf are dominated by carbonate. Our results agree with this and show that this trend also extends across the Rolwey Shelf to the Leveque Rise.

Associations between our sediment data and previous facies models for some areas of the inner shelf are difficult to resolve due to local areas of sparse data. James et al. (1999) observed low amounts of terrigenous sediment on the inner shelf, with an increase in material proximal to river discharge sites (e.g. sediments of the Dirk Hartog Shelf that reflect discharge from the Gascoyne River). Although elevated terrigenous content of sediments may be significant at the scale of these studies and should be noted for planning purposes, our data indicate they are confined to relatively small areas located near the coast and do not significantly affect the sedimentology of the shelf when assessed at a regional scale.

6.1.2. Middle Shelf

At a regional scale, sediments of the middle shelf mostly comprise carbonate sand. Carbonate content increases with sand content. Gravel content is generally low, however large aggregations occur within the Bonaparte Gulf. Jones (1970, 1974) noted that seabed sediments of the middle shelf are coarse and sand dominated, with ~90% carbonate composition. Our results agree with his study and show that the trend extends further south to the extent of the Dirk Hartog Shelf.

At a regional scale the greatest variety of sediments occur in areas containing several geomorphic features (i.e., basins within banks, pinnacles within basins). This is particularly evident where features with a distinct sedimentology are interspersed with other features with a distinct sedimentology (i.e., gravel dominated pinnacles located within the homogenous, sand dominated unassigned shelf).

Our data confirm the aggregation of carbonate on the middle Rowley Shelf. This carbonate deposit contains 80-100% bulk calcium carbonate and is inferred from previous literature as a relict carbonate deposit from the Late Quaternary (James, 2004).

New data for the North West Shelf Transition (NWST) indicates that the area of the middle shelf included in this bioregion has a unique sedimentology compared to the rest of the Northwest margin. For the majority of the NWMR, the middle shelf zone is dominated by carbonate sand. The NWST however is characterised by a high proportion of mud and lower proportion of carbonate. Our data provide further evidence in support of the facies model of Carrigy and Fairbridge (1954), who described this region as showing a distinct change in seabed sediments north of the Leveque Rise. A possible explanation for the distinct change in seabed sediments in the region may be the result of high levels of river discharge and subsequent terrigenous sediment into the Bonaparte Gulf.

6.1.3. Outer Shelf and Slope

Our data indicate that at a regional scale, seabed sediments of the outer shelf and slope are dominated by carbonate sands. Further, mud content increases with water depth on the mid to lower slope. Offshore the shelf break in the NWMR, pre-existing sediment data and facies models are relatively scarce, and our data have characterised much of this environment for the first time. Addition of data in geomorphic features occurring on the outer shelf and slope has facilitated the first quantitative analysis of the sedimentology of features occurring at these water depths in the NWMR, including trenches, reefs and large plateaus and terraces. Sediment data show that some features in this zone are characterised by a distinct sedimentology that differentiates each feature and also forms occurrences of the same feature elsewhere in the NWMR. These features include terraces, ridges and slope.

Our data provides further evidence for extensive carbonate sand deposits at the shelf edge (Carrigy and Fairbridge, 1954). The slope contains a higher proportion of mud (40-80%) than found on the shelf. The Exmouth Plateau is a significant geomorphic feature of the outer shelf and slope and contains 20-60% sand and 40-80% carbonate, also noted in Colwell and von Stackelberg's (1981) facies model.

6.1.4. Abyssal Plain/Deep Ocean Floor

Sediment samples procured for this task from the abyssal plain/deep ocean floor have significantly increased the sample coverage and understanding of the sediment properties. The abyssal plain/deep ocean floor is a relatively homogenous sedimentary environment dominated by siliclastic mud with small inclusions of sand and no gravel. Particle size and bulk carbonate content decreases with increasing water depth, as observed by Colwell and von Stackelberg (1981) and Veevers et al. (1974). Our data support the findings of Colwell and von Stackelberg (1981) who described the sedimentology of the abyssal plain/deep ocean floor as siliceous clay. However, the carbonate content of sediments in deep water areas of the NWMR are now known to be more spatially variable than previously reported with carbonate content as high as 70% locally.

6.2 SEDIMENT TRENDS OF THE NOMINATED AREA OF THE NNMR

New consistent quantitative data for the NNMR have revealed regional scale patterns in sediment distribution not apparent in previous studies and have formed a framework within which local scale patterns can be understood in a regional context. Seabed sediments of the NNMR reflect present day oceanographic conditions and vary in proximity to sources of fluvial and terrigenous material. Sediments are composed of fine- to coarse-grained sand and mud, with carbonate content highest in areas with a high sand content such as the Joseph Bonaparte Gulf. The sedimentology of the Arafura and Sahul Shelves are distinguished from one another based on sediment texture and composition, as discussed below.

Our data indicates that seabed sediments of the Sahul Shelf are sand dominated with localised deposits of gravel on the inner shelf. Carbonate content is high due to the relict carbonate material and extensive outer shelf carbonate banks and facies that characterise the region (van Andel, 1965). Sediment distribution reflects oceanographic conditions and sediments fine with distance offshore. Our data supports the findings of Lees (1992) who described the sedimentology of the Bonaparte Gulf as grading from gravely sand and sandy gravel on the inner shelf to sand on the middle shelf and clayey sand on the outer shelf, a pattern that reflects a seaward decrease in tidal velocity (Lees, 1992).

The sedimentology of the Arafura Shelf, as described from our sediment data, is dominated by mud with localised accumulations of sand and gravel. Carbonate content is relatively low (mostly <20%) and increases towards the shelf edge/upper slope and with distance from sources of terrigenous input. This trend is consistent with Jongsma's (1974) sediment model of the Arafura Shelf which illustrates the high mud and low carbonate content of the middle shelf region. Our data quantitatively characterises the shelf break and slope beyond the Arafura Shelf for the first time, showing the region is sand dominated with small and localised gravel deposits.

6.3. IMPLICATIONS FOR MARINE HABITAT MAPPING

Conservation of benthic marine habitats requires information on the geomorphology, sedimentology and oceanography of an area. The use of sediment properties as physical surrogates for benthic biological data that can be measured with ease (Bax, 2001) and may provide a greater understanding of marine ecosystems (Post *et al.*, 2006 and Post, 2006). Relationships are recognised to exist between the texture and composition of seabed sediments and biota (Day, 2000; Kostylev, 2001; Roff, 2003; Roff, 2000). For this reason, sediment properties as measured in this study are an important input into statistical models used to approximate the nature and extent of seabed marine habitats (see the seascapes of Day and Roff, 2000). The accuracy of the seascapes in representing seabed habitats is directly related to the quality and resolution of underlying sediment data. Major sources of spatial error in sediment data used to characterise habitats are the result of low data density and inadequate interpolation methodologies. Addition of new data reduces these sources of error and allows recognition of relationships between physical datasets that are useful in developing more effective interpolation techniques.

Benthic biota have been shown to have measurable relationships with the gravel and mud content of seabed sediments (Post *et al.*, 2006; Bax, 2001). Our data show that where the sedimentology is relatively diverse, such as on the inner shelf and in submarine canyons, the sediment properties including gravel and mud content vary over relatively small distances. A much higher sample density is required in these environments to more accurately map the spatial distribution of the sediment properties (and by association benthic biota). Our data have improved sample coverage in these areas; however, additional coverage will further increase the reliability in which this can be mapped. In areas where seabed environments are relatively uniform, such as over most of the abyssal plain/deep ocean floor, sediment properties are more constant over larger distances and can be accurately mapped from fewer samples.

Our synthesis of sedimentology and geomorphology has; 1) provided a more comprehensive understanding of the range of seabed sedimentary environments present in the NWMR, 2) allowed comparison between sedimentary environments occurring in different areas culminating in the identification of rare or unique areas of seabed that may be of particular interest for conservation, and 3) described relationships between physical datasets providing full coverage of the NWMR, such as bathymetry and geomorphology, and sediment distribution. These can be used to predict the sedimentary environments that occur in areas where sediment data points are relatively scarce. New data on the abyssal plain/deep ocean floor have allowed characterisation at a higher confidence.

6.4. LIMITATIONS

Although we have added significant detail to the regional sedimentology of the northwest margin, including better defined local and regional trends, the data are still relatively sparse which limits the degree to which we can fully describe the sedimentology. It is important to recognise some of the limitations of the data.

Data in the NWMR is clustered around the middle shelf region, with a paucity of data located on the inner shelf and abyssal plain/deep ocean floor. This means that sediments present in areas with most data are likely to be overstated in descriptive statistics at a regional scale. Uneven distribution of data also makes it difficult to statistically quantify relationships that are observed visually in data and means that existing relationships may not be detected and utilised when interpolating data to rasters for input into seascapes processes. While this may cause some inaccuracy or bias at a regional scale, the structure of our analysis with observations and statistics generated for individual bioregions, provinces and features means that sedimentology at these scales is not significantly affected. Because data density is greatest on the middle to outer shelf we are confident that sediment patterns in this location are real. However, complexity elsewhere may not have been detected due to relatively low sample density.

In this study we have used the inverse distance weighted method with a fixed interpolation parameter, which has been used by Geoscience Australia to interpolate all of its point data across Australia's marine jurisdiction. This provides for a comparable and consistent dataset.

The maximum distance that any data were extrapolated was 45 km. This method is adequate, where large ranges in data density occur, to produce maps that allow identification of trends in sediment distribution occurring at a regional scale, but it is likely to inaccurately represent sediment distribution at finer scales.

The key question in modelling studies is "*How much simplification is acceptable?*" A linear inverse distance weighted method (with a fixed interpolation parameter) does not necessarily represent all trends in sediment distribution. However, no interpolation method is able to pick up such trends if sample density is inadequate. Trends in sediment distribution in the NWMR are known to occur on scales from centimeters to hundreds of kilometers. Without knowing at what scale variations in sediment characteristics are significant in mapping distribution of species, it is difficult to comment on how much uncertainty in interpolated data affects results generated for seabed habitat mapping.

Sample density for the NWMR is 1:700 km^2 on the shelf, 1:1,200 km^2 on the slope, 1:19,100 km^2 on the rise and 1:10,100 km^2 on the abyssal plain/deep ocean floor. This provides the minimum distances over which variations in the sediment properties can be detected. Interpolation images must be used with caution when drawing comparison between seabed composition in different areas of the NWMR as they do not necessarily; 1) represent the relative proportions of environments present in an area; or 2) the way sedimentary environments are interspersed spatially, as resolution of the interpolation is more a reflection of sample density than diverse sedimentology.

6.5. RECOMMENDATIONS

To improve interpolated data it is important to improve sample densities in areas of the seabed that contain significant variations in sediment characteristics over relatively small distances. As collecting sediment samples from the seabed is highly time consuming and costly, information about seabed complexity and the relationship to geomorphology can be used to target areas where data coverage is likely to be inadequate. New data generated for the NWMR and the SWMR (Potter, 2006) allow recognition of relationships between relatively diverse seabed sedimentology and geomorphic features including canyons and pinnacles. In the NWMR, sample densities in these features remain relatively low. New data for the NWMR also indicate that although sediments are more homogenous in deep water areas (e.g., abyssal plain/deep ocean floor), greater variation may be captured in these areas than is captured in the current data. Data generated for this study have significantly improved sample densities for these areas and this work should be continued, particularly for the abyssal plain/deep ocean floor, lower slope and rise.

Data collection, advances in interpolation methods, and improved understanding of relationships between geomorphic features and sediment type will improve the accuracy of future sedimentology work conducted at a regional marine planning area scale. An improved understanding of geomorphic features such as the abyssal plain/deep ocean floor is required to most accurately map sediment distribution. Where sample coverage is sparse, the inclusion of secondary datasets in the interpolation process will allow the prediction of sediment type. Secondary datasets such as energy level, tidal regime, sediment transport pathways, and previous sediment models will improve the accuracy of future seabed sediment mapping. Our study has shown that future sampling in the NWMR should focus on areas with poor sample coverage such as the abyssal plain/deep ocean floor, pinnacles, trenches, inner shelf, lower slope and rise.

Geoscience Australia has a research program to assess the accuracy and precision of interpolation techniques and is investigating the usefulness of secondary datasets during interpolation.

6.6. SUMMARY

The NWMR and NNMR are characterised by a variable geomorphology and sedimentology. Sediment texture and composition displays a zoning with depth, and sand and gravel dominate the shelf area whilst mud dominates the lower slope and abyssal plain/deep ocean floor. Calcium carbonate concentrations throughout the region are generally highest along the shelf to the shelf edge and are associated with reefs. Significant geomorphic features of the NWMR and NNMR include; pinnacles, shallow water and deep water terraces, slope, rise, trenches/troughs, shallow water and deep water plateaus, deeps/holes/valleys, slope, shelf and banks/shoals of the Joseph Bonaparte Gulf.

Geoscience data plays a vital role in the management of Australia’s ocean resources because we may never have a full inventory of all biota found on the seabed particularly for deep sea regions. Geomorphology and sedimentology data can be mapped economically and the data can be used to infer relationships between the distribution and abundance of benthic biota. The relationship(s) between geomorphology and sediment/substrate type and biota is a key priority for research associated with the implementation of Bioregional Marine Planning Areas.

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8. Appendices

8.1. APPENDIX A: PROJECT STAFF

Name	Substantive Role
Dr Andrew Heap	Project Manager/Geomorphologist/Sedimentologist
Anna Potter	Project Scientist/Sedimentologist
Christina Baker	Project Scientist/Sedimentologist (DEWHA funded)
Maggie Tran	Project Scientist/Sedimentologist (DEWHA funded)
Christian Thun	Laboratory Manager
Tony Watson	Senior Laboratory Officer
Alex Mclachlan	Senior Laboratory Officer
Billie Poignand	Laboratory Officer
Keith Henderson	Laboratory Officer
Kylia Wall	Laboratory Officer (DEWHA funded)

8.2. APPENDIX B: MAPPING PARAMETERS

8.2.1. Gravel, Sand, Mud and Carbonate Maps

- data imported to ArcGIS in csv format
- interpolate to raster using:
  - i) inverse distance weighted interpolator
  - ii) cell size of 0.01 decimal degrees (dd) – about 1 kilometre
  - iii) optimal parameters: search radius of 12 points and power parameter of 1 (Ruddick, 2006).
  - iv) maximum extrapolation distance of 0.45 dd – about 45 kilometres
- raster image clipped to Australian Economic Exclusive Zone limit and the National Mapping 1:250,000 coastline from the National GIS.
- additional clip areas were added where interpolator extrapolation produced
- artefacts that were not consistent with the surrounding data points.

8.2.2. Seabed Sediment Type – Folk Classification

- rasters for fractions were created as in #.2.1 but with a cell size of 0.05dd.
- rasters were exported as 0.05 dd grids of points
- samples were allocated to one of 15 Folk sediment type classifications based on gravel/sand/mud percentages using pearl script.
- classified data was imported into ArcGIS in .csv format
- point data was converted to raster with folk class number as the cell value

8.2.3. Sediment Texture – Red/Green/Blue Image

- rasters for fractions (#.2.1) were imported into ENVI
- grids were loaded into the bands of a RGB image (Gravel – red, Sand – green, Mud – blue)
- image was saved as a geotiff and imported to ArcGI

8.3. APPENDIX C: EXPLANATION OF TABLE FIELDS

8.3.1. Chapter 4 Tables

E.g. Table 4.1

Feature	Area in NWMR	% total* NWMR Area	% EEZ Area	% Total EEZ area located in NWMR	Water Depth Range** in NWMR (m)

Area in NWMR: Area in km² covered by this feature within the NWMR.

% total* NWMR Area: Percent of the total area of the NWMR (not including areas with water depths <10 m) which is allocated to this feature.

% EEZ Area: Percent of the total area of the EEZ which is allocated to this feature.

% Total EEZ area located in NWMR: The proportion of the EEZ area allocated to this feature that lies within the NWMR.

Water Depth Range in NWMR (m):** Range of water depths occurring in the NWMR area (not including areas with water depths <10m) allocated to this feature. To reduce error, depths were determined from the point data underpinning the bathymetry grid rather than the interpolated data. Values are rounded to the nearest 10 m.

E.g. Table 4.2

PROVINCE/ # Feature	No. sample points	% NWMR Area	Average sample density

PROVINCE/ # Feature: Features are nested within Provinces. Shelf, Slope, Rise and Abyssal Plain/Deep Ocean Floor Provinces are capitalised. Statistics for Provinces include the area of all features occurring within them. Feature names are not capitalised. Shelf, slope, rise and AP/DOF features comprise the area of these provinces with no other features identified within them.

No. sample points: The total number of samples used in this study that are located within the area allocated to this province or feature. Some samples included in this figure have only textural or compositional data.

%NWMR Area: As in Table 4.1.

Average sample density (samples per km²): The average sample density across all occurrences of the feature in the NWMR. This is calculated by dividing the total area of the feature by the number of sample points within it. Results have been rounded to the nearest 100 km².

8.3.2. Chapter 5 Tables

E.g. Table 5.1

Bioregion	No. sample points (no. added for task)	% NWMR Area*	Average sample density (km²)

No. sample points (no. added for task): The number of sample points occurring in the bioregion including both data existing before this task and new assays generated for this task. The number of samples added to this bioregion for this task is given in brackets.
%NWMR Area: Percentage of the total area of the NWMR allocated to this bioregion. Percentages are calculated from the NWMR including the area not assigned to any bioregion.
Average sample density (km^2): As for Table 4.2.

E.g. Table 5.2

Feature	% of bioregion area covered	% of NWMR area this unit lies within this bioregion	% of EEZ area this unit lies within this bioregion

% of bioregion area covered: The percentage of the total area of the bioregion that is included in the NWMR that falls within this feature. Calculations do not include areas with water depths <10 m.

% of NWMR area this unit lies within this bioregion: The percentage of the total area covered by this feature in the NWMR that lies within the area of this bioregion included in the NWMR.

% of EEZ area this unit lies within this bioregion: The percentage of the total area covered by this feature in the EEZ that lies within the area of this bioregion included in the NWMR.

E.g. Table 5.3

Feature	Depth Range (m)	Mean Depth (m)

Depth Range (m): Range of water depths occurring in the area of this feature within the bioregion(not including areas with water depths <10 m). To reduce error, depths were determined from the point data underpinning the bathymetry grid rather than the interpolated data. Values are rounded to the nearest 10 m.

Mean Depth (m): The mean water depth occurring in the area of this feature within the bioregion. To reduce error, depths were determined from the point data underpinning the bathymetry grid rather than the interpolated data. Areas with water depths <10 m were removed prior to calculations. Values are rounded to the nearest 10 m.

8.4. APPENDIX D: METADATA

(To be included with GIS files in final report DVD)

8.5. APPENDIX E: DATA GENERATED

See excel workbook "NWMR Task 2007 assays".

8.6. APPENDIX F: LASER GRAINSIZE DISTRIBUTIONS

See pdf file "Appendix F NWMR Laser".

8.7. APPENDIX G: WEB ACESSIBLE DIGITAL MAPS FOR DATA COVERAGE AND SEDIMENT PROPERTIES

(To be included in final report DVD)