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Inter-reefal Seabed Sediments and Geomorphology of the Great Barrier Reef, a Spatial Analysis

Emma Mathews, Andrew Heap & Murray Woods

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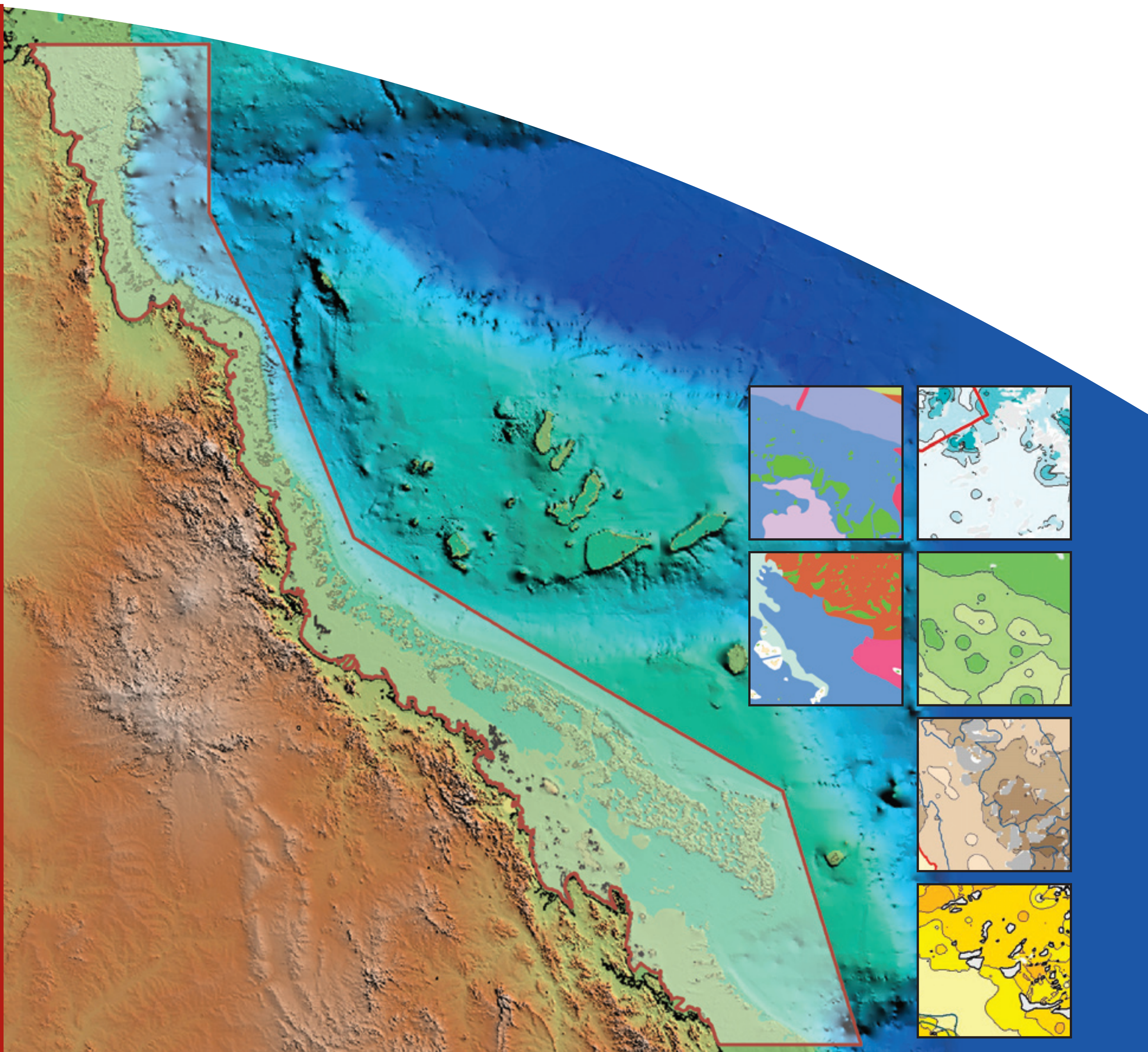

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Inter-reefal seabed sediments and geomorphology of the Great Barrier Reef, a spatial analysis

Emma Mathews, Andrew Heap and Murray Woods

Marine Coastal and Environment Group, Petroleum and Marine Division, Geoscience Australia, GPO Box 378, Canberra, Australia

Australian Government

Geoscience Australia

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Correspondence for feedback:
Andrew Heap
Geoscience Australia
GPO Box 378
Canberra
ACT 2601

Andrew.Heap@ga.gov.au

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Executive Summary

Inter-reefal (i.e. non-reefal) seabed environments have been much less studied than the coral reefs, however they comprise 95% of the total Great Barrier Reef (GBR) Marine Park area. Regional scale spatial analysis of the sediments and geomorphology in these areas allows for a systematic characterisation of the seabed, where comprehensive biological datasets are lacking. We offer an up-to-date synthesis of inter-reefal environments in the GBR, to better understand the nature and distribution of seabed habitats at a regional scale and within the current planning zone scheme, in support of Marine Park management.

New quantitative information about surface sediments and geomorphic features, together comprise a new physical dataset of the GBR seabed. This regional dataset contains over 3,000 sediment samples available in Geoscience Australia's (GA) national marine samples database, MARS (www.ga.gov.au/oracle/mars), substantially improving the coverage of surface sediment data from inter-reefal areas, and; GA's current Geomorphic Features dataset (Harris et al., 2005) of the seabed morphology. This marks the first regional synthesis of the surface sedimentology and geomorphology of the GBR since the pioneering work of Belperio (1983a, 1983b) and Maxwell (1968; 1969a; 1969b; 1973).

We present a new quantitative sediment dataset that shows regional trends in surface sediments; refining the existing facies model for the mixed carbonate-siliciclastic GBR margin. Our findings also reveal local scale facies characteristics, within the broader regional trends. Until now these distribution patterns haven't been identified on the GBR shelf and are considered to be an important characteristic of the region. In addition, we have revealed other sedimentary characteristics of the region;

- Low gravel concentrations cover extensive parts of the shelf. Patches of high gravel concentration occur locally on parts of the inner and outer shelves, reflecting the input of gravel from reef talus aprons. These areas may also be associated with strong tidal currents.
- Sand is the dominant grain size fraction, and highest concentrations occur on the middle and outer shelves. Although continuous regions of high sand concentration occur in the far north (e.g. Cape York) and south (e.g. south of Broad Sound) of the Marine Park, the overall distribution of sand is variable as changes in concentration produce local, small-dimension patches at a scale of 10's of metres.
- The patchy distribution of sand may reflect a mixture of; 1) widespread supply of modern skeletal carbonate grains, such as foraminifera, molluscs and *Halimeda*, and/or restricted supply of relict sand; and, 2) the effects of hydrodynamic irregularities in inter-reef channels.
- High mud concentrations predominantly occur along the inner shelf and slope. Mud forms local patches on the inner shelf associated with fluvial point sources, which are spatially discontinuous, producing a regionally variable terrigenous sediment wedge of coalescing mud (and sand) patches.
- Surface sediments are carbonate-dominated across the shelf and broadly display a regional north-south, shelf-parallel zonation pattern. Low carbonate concentrations of <40% on the inner shelf denote high terrigenous compositions, which increase to >80% on the outer shelf. Within the regional zonation pattern, carbonate patches locally produce a variable distribution in sediment composition.

- Uniformly high concentrations of bulk carbonate and carbonate mud on the outer shelf, reflect the constant supply of skeletal carbonate grains from inter-reefal environments, in areas of high reef density and the negligible influence of fluvial sediments on the outer shelf.

Regional variations in seabed sediments and geomorphology across the region are also evident in the physical character of the planning zones. By quantifying the substrate in each planning zone type, we provide fundamental baseline information to improve environmental management and the monitoring of seabed habitats. Overall, the planning zones are characterised by several sedimentary environments, which include;

- Sand- and carbonate-rich sediments around islands and reefs occurring on the middle and outer shelves.
- Gravel- and mud-rich sediments, with low carbonate compositions in slope areas.
- Slightly muddy with low to moderate carbonate concentrations on the inner shelf and continental slope regions.
- Mud-rich, gravel- and carbonate-poor sediments in river-influenced regions on the inner shelf.

The majority of planning zone types contain high (>60%) sand concentrations, reflecting the extensive inter-reefal areas on the shelf. Scientific Research, Preservation and Habitat Protection Zones all contain high bulk carbonate, carbonate sand and carbonate mud contents, which coincide with reef-dominated areas. High carbonate sediments occur on the mid to outer shelves, and terrigenous-dominated sediments occur in planning zones on the inner shelf, which emulate the regional sediment model. Buffer Zones contain the highest mean gravel concentrations, which may be associated with rocky substrates on the continental slope. This quantitative spatial analysis of the physical characteristics of the current planning zones enables us to develop our understanding of the diversity of the seabed in these zones, and may allow us to predict habitat distributions where there is a scarcity of biological data.

Acknowledgements

Murray Woods produced the original sediment attribute maps and spatial layers of the sediments and geomorphic features in the GBR planning zones. Many thanks to the Geospatial Applications and Visualisation Unit, Geoscience Australia, in particular Terry Brown and Veronika Galinec for their re-production of the figures. Richard Brown, Tony Watson, James Bowles and Robbie Morris of the Sedimentology Laboratory at Geoscience Australia managed sample analysis of the recently acquired GBR samples and are thanked for their efficient production of the texture and composition data. We thank CSIRO and AIMS for their collaboration on this project, and in particular Dr. Roland Pitcher (CSIRO) who reviewed the Introduction and Methods chapters. The authors would like to thank David Ryan of Geoscience Australia and Dr. John Marshall for their detailed reviews of the original text. This record is published with permission of the Chief Executive Officer, Geoscience Australia.

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1. Introduction

1.1. BACKGROUND

This study provides an up-to-date synthesis of the regional sedimentology and geomorphology of the inter-reefal / lagoonal (non-reefal) seabed of the Great Barrier Reef (GBR) Marine Park region, using new and previously acquired data. The inter-reefal environment comprises 95% of the area of the entire GBR and forms an interconnected network of seabed habitats that support a range of benthic communities (Chin, 2003; Pitcher et al., 1997). As such, the inter-reefal seabed is a key component of the GBR ecosystem. But despite this fact, it has been much less studied than reefal areas. This study will improve our understanding of the nature of inter-reefal environments of the GBR, and their significance for benthic habitats and marine park zoning.

We have carried out a comprehensive characterisation of the GBR seabed based on quantitative spatial analysis of seabed sediment. Interpretations presented here are based on grainsize and carbonate analysis of sediment samples from the GBR marine park. More than 1,000 new sediment samples were acquired during regional-scale seabed surveys of the GBR, conducted in 1991-1992 and 2003-2005. Almost 2,000 additional samples were obtained from previous studies, and are contained in the Geoscience Australia (GA) national marine samples database: MARS (www.ga.gov.au/oracle/mars). Together, this sample database provides the first comprehensive assessment of the regional surface sedimentology and geomorphology of the GBR since Maxwell's pioneering work in the late 1960's and early 1970's (Maxwell, 1968; 1969a; 1969b; 1973).

This report has been compiled in support of the federal government's regional marine planning program, to provide fundamental baseline scientific information on the nature of the different management zones in the Great Barrier Reef World Heritage Area (GBRWHA). This study also contributes to the GBR Seabed Biodiversity Project of the CRC Reef (Project C1.1.2) (e.g. Pitcher et al., 2002).

1.2. REGIONAL SETTING

The GBR occupies approximately ~270,000 km^2 of the continental shelf on the northeast margin of Australia (Figs. 1.1 and 1.2). It is the largest modern tropical carbonate-siliciclastic province on earth (Belperio and Searle, 1988; Dunbar et al., 2000), and is dominated by a discontinuous tract of approximately >2,900 coral reefs that extend from Torres Strait in the north to Lady Elliot Island (east of Gladstone) in the south, a distance of approximately >2,200 km (GBRMPA, 2006). The shelf thus consists of a shore-parallel, rimmed carbonate platform and lagoon <90 m deep that extends along Australia's northeast margin (Belperio, 1983).

Surface sediments of the central GBR have been broadly divided into three distinct shelf-parallel facies that coincide with water depth (Belperio, 1983), namely: 1) an inner shelf zone from 0-20 m dominated by terrigenous sediment; 2) a middle shelf zone from 20-40 m of mixed carbonate-siliciclastic sediment; and 3) an outer shelf zone from 40-~90 m of carbonate-dominated sediment (Fig. 1.3) (Belperio and Searle, 1988). Existing sediment models for the GBR indicate that present-day terrigenous sediments are derived from river point sources such as the Burdekin River, and are trapped near the coast and commonly deposited close to river mouths (e.g., Belperio and Searle, 1988; Orpin et al,

Figure 1.1. Location map showing the Great Barrier Reef region and extent of the Marine Park, with the location of features mentioned in text. The Marine Park boundary and the four large management areas are highlighted in red. The boundary of Australia's Exclusive Economic Zone (EEZ) is shown in black.

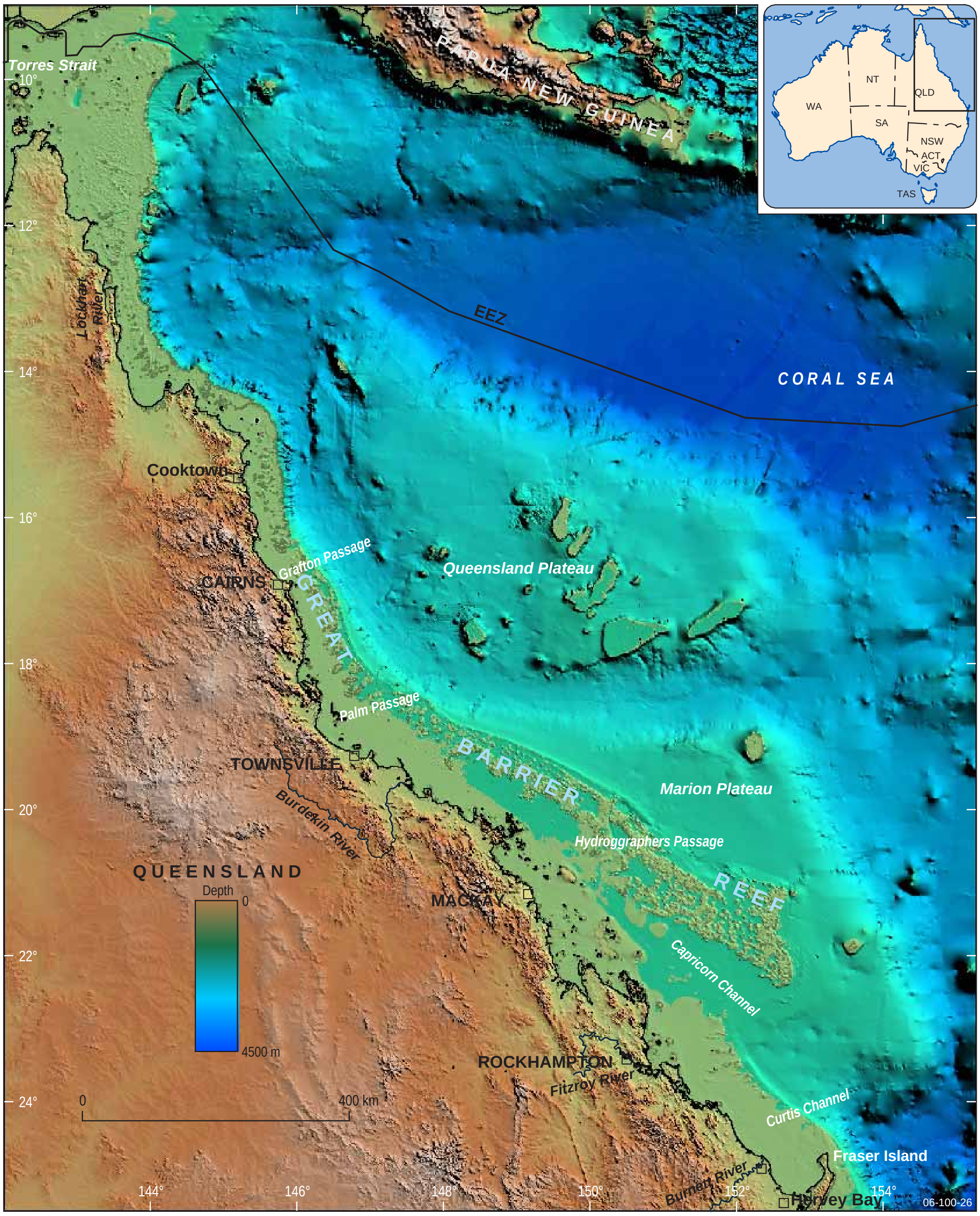

Figure 1.2. False-colour image showing the gross geomorphology and bathymetry of the north eastern margin of Australia, with some of the major geomorphic features labelled. It includes seabed environments from the continental shelf lagoon, shelf edge reefs and deep water continental slope.

1999; 2004). However, stored lowstand siliciclastic sediments on the middle shelf are reworked to provide an additional sediment source on the modern GBR shelf (Heap et al., 2002). Carbonate sediments are derived from the production and break-down of numerous carbonate-secreting organisms, and are mainly composed of the skeletal

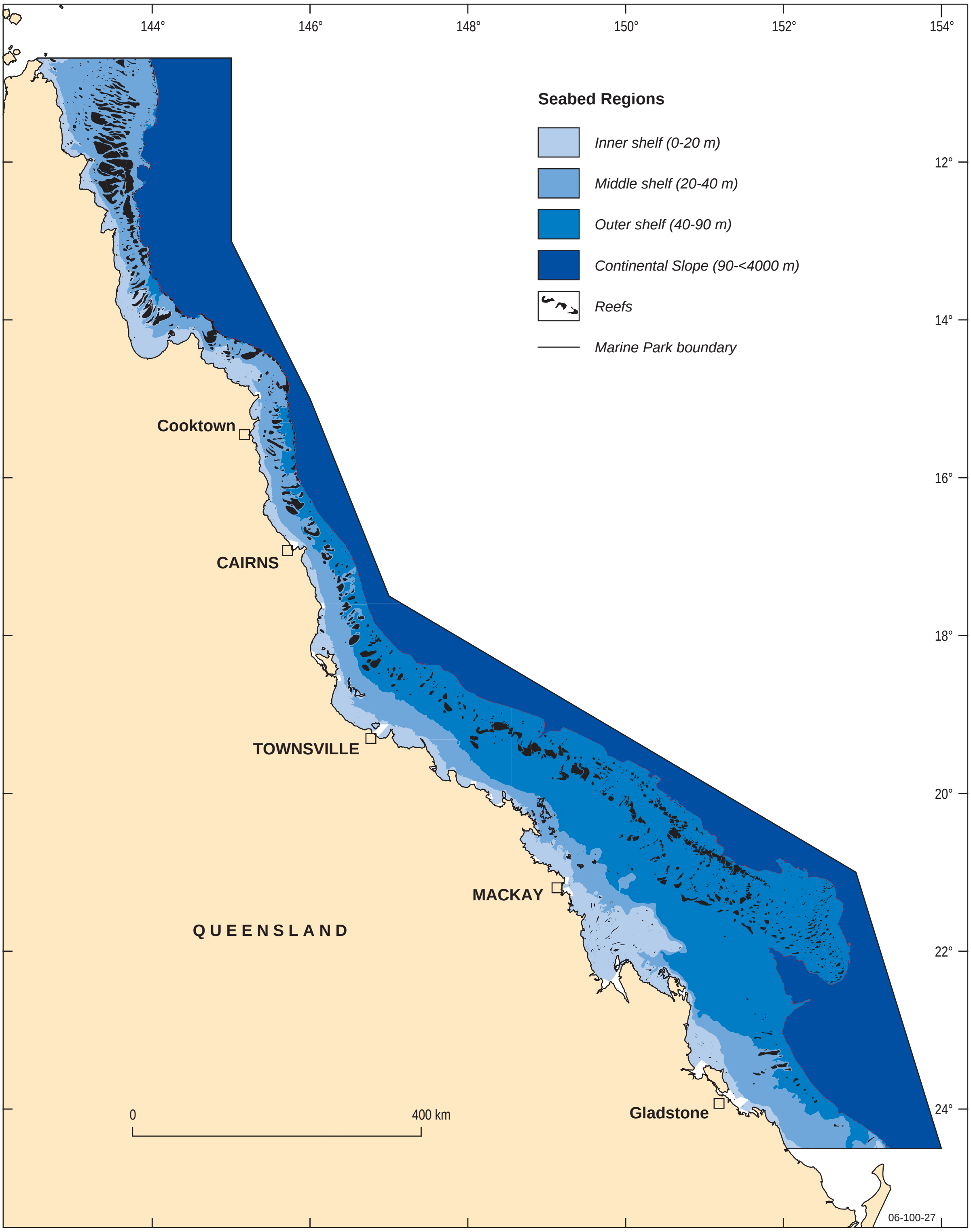

Figure 1.3. Map showing the definition of the continental shelf and slope within the Marine Park. Subdivision of the shelf into an inner shelf, from 0-20 m water depth, a middle shelf, from 20-40 m water depth and outer shelf, from 40-90 m water depth is derived from Belperio's (1983a) shelf-parallel sediment distribution pattern. All blue areas highlight inter-reefal seabed environments within the Marine Park, and reefs are shown in black.

remains of foraminifers, molluscs, bryozoans and corals, as well as minor amounts of the coralline alga *Halimeda* (Maxwell, 1968; Maxwell and Swinchatt, 1970; Belperio and Searle, 1988; Flood and Orme, 1988; Heap et al., 2001; Dunbar and Dickens, 2003).

On the inner-shelf, sediment dispersal is predominantly towards the NW in an along-shelf direction (Lambeck and Woolfe, 1998; 2000). The sediments are transported by a strong and predominant NW-directed along-shore current that is generated by the SE trade winds between March and October (Belperio and Searle, 1988; Wolanski, 1994). In some areas between the islands and reefs, strong tidal currents scour the seabed, often exposing the underlying rock. Tropical cyclones generate very strong currents that cause local sediment redistribution and substrate erosion, and control river flood plumes and sediment dispersal on the middle and outer shelves (Larcombe et al., 1995; Gagan et al., 1988; Orpin et al., 1999; Larcombe and Carter, 2004).

1.3. MARINE PARK ZONING AND MANAGEMENT

The GBRWHA is a multiple use Marine Protected Area (MPA) and is currently the largest world heritage area in existence, covering almost 350,000 km^2 (Fig. 1.1) (GBRMPA, 2005). The Great Barrier Reef Marine Park Authority (GBRMPA) manage planning and development of the GBRWHA under the GBR Marine Park Zoning Plan which was first implemented in the mid 1980's (GBRMPA, 2003). This plan covers all activities and promotes the ecologically sustainable use of the GBR (Fig. 1.4). It also aims to protect representative areas of biodiversity within the GBR ecosystem. However, currently inter-reefal areas are under represented in protected areas (Pitcher, 1997). The existing marine park zoning plan specifies eight management zones which permit different uses of the park, namely: 1) General Use Zone; 2) Habitat Protection Zone; 3) Conservation Park Zone; 4) Buffer Zone; 5) Scientific Research Zone; 6) Marine National Park Zone; 7) Preservation Zone; and 8) Commonwealth Islands Zone (Fig. 1.4). These marine park zones complement mainland and island national parks (GBRMPA, 2005).

The current zoning scheme aims to protect and preserve biodiversity through the declaration of a network of no-take zones that together attempt to capture the range of habitats and biological communities contained in the Marine Park (GBRMPA, 2005; Day et al., 2002). High-quality physical information including: sedimentology, geomorphology, and oceanography can assist in the definition and validation of zone boundaries, as the physical environment provides a "context" within which ecological processes function (Heap et al., 2005). Physical information can assist managers with the development of solutions to current management issues affecting marine habitats and communities in the GBR.

1.3.1. Management

Several key management issues threaten the GBR ecosystem, its biodiversity and the health and functioning of lagoonal and inter-reefal environments. Changes such as sea level rise and increased water temperatures, and anthropogenic impacts such as trawling, dredging for shipping, and increased catchment run-off, threaten to modify the physical substrate of the seabed. The magnitude and extent of these impacts are poorly understood due to a lack of regional monitoring of lagoonal and inter-reefal seabed areas and a lack of high quality baseline data.

Natural fluctuations in the health of the GBR ecosystem are recognised to have occurred prior to European settlement (Wolanski and De'ath, 2005). However in some cases, the modern decrease in coral cover is a direct result of present land use practices (Wolanski and De'ath, 2005). Modification or enhancement of sediment supply can have

ACTIVITIES GUIDE
(see relevant *Zoning Plans* and *Regulations* for details)

	General Use Zone	Habitat Protection Zone	Conservation Park Zone	Buffer Zone	Scientific Research Zone [2]	Marine National Park Zone	Preservation Zone
Aquaculture	Permit	Permit	Permit [1]	✗	✗	✗	✗
Bait netting	✓	✓	✓	✗	✗	✗	✗
Boating, diving, photography	✓	✓	✓	✓	✓ [2]	✓	✗
Crabbing (trapping)	✓	✓	✓ [3]	✗	✗	✗	✗
Harvest fishing for aquarium fish, coral and beachworm	Permit	Permit	Permit [1]	✗	✗	✗	✗
Harvest fishing for sea cucumber, trochus, tropical rock lobster	Permit	Permit	✗	✗	✗	✗	✗
Limited collecting	✓ [4]	✓ [4]	✓ [4]	✗	✗	✗	✗
Limited spearfishing (snorkel only)	✓	✓	✓ [1]	✗	✗	✗	✗
Line fishing	✓ [5]	✓ [5]	✓ [6]	✗	✗	✗	✗
Netting (other than bait netting)	✓	✓	✗	✗	✗	✗	✗
Research (other than limited impact research)	Permit	Permit	Permit	Permit	Permit	Permit	Permit
Shipping (other than in a designated shipping area)	✓	Permit	Permit	Permit	Permit	Permit	✗
Tourism programme	Permit	Permit	Permit	Permit	Permit	Permit	✗
Traditional use of marine resources	✓ [7]	✓ [7]	✓ [7]	✓ [7]	✓ [7]	✓ [7]	✗
Trawling	✓	✗	✗	✗	✗	✗	✗
Trolling	✓ [5]	✓ [5]	✓ [5]	✓ [5,8]	✗	✗	✗

PLEASE NOTE: This guide provides an introduction to Zoning in the Great Barrier Reef Marine Park. Relevant Queensland Marine Park Zoning Plans or the Queensland Environmental Protection Agency should be consulted for confirmation of use or entry requirements.

1. Restrictions apply to aquaculture, spearfishing and harvest fishing for aquarium fish, beachworm and coral in the Conservation Park Zone.
2. Except for One Tree Island Reef (SR-23-2010) and Australian Institute of Marine Science (SR-19-2008) which are closed to public access and shown as orange, all other Scientific Research Zones are shown as green with an orange outline.
3. Limited to 4 catch devices (eg. crab pots, dillies and inverted dillies) per person.
4. By hand or hand-held implement and generally no more than 5 of a species.
5. Maximum of 3 lines/rods per person with a combined total of 6 hooks per person.
6. Limited to 1 line/rod per person and 1 hook per line. Only 1 dory detached from a commercial fishing vessel.
7. Apart from traditional use of marine resources in accordance with s.211 of the *Native Title Act 1993*, an accredited Traditional Use of Marine Resources Agreement or permit is required.
8. Pelagic species only. Seasonal Closures apply to some Buffer Zones.

Detailed information is contained in the Great Barrier Reef Marine Park Zoning Plan and Regulations.

- Permits are required for most other activities not listed above.
- Commonwealth owned islands in the Great Barrier Reef Marine Park are zoned "Commonwealth Islands Zone" - shown as cream.
- All Commonwealth Islands may not be shown.
- Special Management Areas may provide additional restrictions at some locations.
- The Zoning Plan does not affect the operation of s.211 of the *Native Title Act 1993*.

ACCESS TO ALL ZONES IS PERMITTED IN AN EMERGENCY.

Figure 1.4. The Great Barrier Reef Marine Park Authority Activities Guide (reprinted from GBRMPA).

direct consequences for other parts of the seabed environment; affecting benthic processes, habitat structure, and, potentially marine diversity (GBRMPA, 2005; Zann and Brodie, 1997). Hence, to develop our understanding of these complex interactions, undertaking integrated science using comparable physical and biological datasets is important to future planning and management of the GBR system.

1.3.2. Seabed characterisation and monitoring

Seabed environments can be characterised by quantifying the physical attributes of the substrate. Such physical attributes include the distribution, composition and texture of surface sediments and geomorphic features. The complexity and heterogeneity of the substrate influence the distribution of biological communities, and form a foundation for ecosystems and living biological components. Geological and physico-chemical processes operating within the substrate directly influence the functioning of surface ecosystems (Zektser, 2006). Thus, changes in the structure/composition of the substrate may instigate changes in biological communities that inhabit the substrate, such as soft bottom communities in inter-reefal areas of the GBR.

The regional distribution of surface sediments and facies types provides baseline physical data from which other parameters can be predicted. From this data is may be possible to establish known, previous and potential distributions of physical attributes. The assessment of natural or anthropogenic impacts/changes to biological communities and ecosystems can be monitored using baseline data. Long term changes in surface sediment patterns may be predicted from broad trends in surface sediments and by way of refining the existing sediment facies model of the GBR (e.g. Belperio, 1983a). Sediment facies and substrate type (i.e. gravel, sand, mud attributes) can be broadly used as a surrogate for understanding current distributions and changes of biota. The relationship between the type of substrate and composition of seabed biota in the GBR has been previously detected by other workers (e.g. Pitcher et al., 2002; Post et al., 2006).

Physical sediment data can be systematically acquired over large areas, providing a broad-scale, first-order seabed/habitat characterisations that can be used for conservation mapping. It is possible for broad scale trends in physical characteristics to be recognised from regional sampling; hence data collection can take place at lower resolution than for biological assemblages. Physical attributes can be spatially quantified to give the broad scale heterogeneity, range and physical diversity (i.e. uniqueness/vulnerability) of inter-reefal seabed environments in the GBR ecosystem. At this sample resolution scientists can quantitatively monitor changes over time at a more rapid rate than for biological sampling.

Quantitative physical information may also provide insights into the stability (i.e. change) and vulnerability of seabed habitats in space and time. An understanding of the steady-state environment of the GBR lagoon requires continual monitoring to identify changes and instability. It is essential that baseline information on the physical properties of the seabed are further explored as a means of evaluating, identifying or predicting a steady-state seabed/habitat character, from an unstable one.

While the synthesis contained in this record provides a more comprehensive definition of seabed character for the non-reefal environment of the GBR, and the physical data provides valuable information on the nature of seabed environments, we must be careful not to presume that benthic biodiversity can be estimated or classified based solely on physical variables (e.g., Snelgrove and Butman, 1994). These data should be used with other biological and physical datasets to thoroughly capture the biodiversity of the non-reefal seabed environments of the GBR.

1.4. REPORT AIMS AND STRUCTURE

The principal aim of this study is to provide a regional assessment of the sedimentology and geomorphology of lagoonal and inter-reef seabed environments of the GBR. Outcomes of this work include an improved understanding of the nature of these environments, and an appreciation of the significance of these environments for quantifying seabed diversity in the GBR. The physical information contained in this report is relevant to managers, planners and scientists with interests in the GBR. The main aims of this report are to:

1. describe and interpret the broad textural and compositional features and distribution patterns of surface sediments in the GBR;
2. create a new regional surface sediment facies map of the GBR based on the most up-to-date and comprehensive sedimentary and geomorphic datasets available, to add to the current knowledge of the physical environments on the northeast Australian shelf;
3. describe the key physical characteristics of select management zones in the existing GBRMPA management plan and assess the physical diversity of seabed in each management zone via statistical analyses of the data; and
4. illustrate how the physical data can be used to assist in making informed decisions about key management issues in the GBR.

The report is structured into three broad sections that reflect the main aims and objectives of the study. First, the existing sedimentology and geomorphology of the GBR is described and reviewed to provide the framework for the newly acquired data and its application to seabed classification (Chapters 1 and 2). The second section (Chapter 4), presents the formulation of the new facies model for the GBR, based on a broad synthesis of all the sediment and geomorphic data. This work provides an innovative explanation of the surface sedimentology, using the most up-to-date and comprehensive dataset for the GBR. The third section (Chapter 5) puts the physical data into the context of the existing GBRMPA planning zones. Lastly the results are discussed and summarised in terms of their wider implications for management and regional marine planning through the use of examples (Chapter 6).

2. Previous Work

This chapter provides an overview of key geoscience research that has been undertaken in the GBR province to date, providing a context for the seabed characterisation work described this report. Four main themes are discussed, namely: geological setting, Late Quaternary history, geomorphology and sedimentology, and oceanography.

2.1 GEOLOGICAL SETTING

2.1.1 Tectonics

Australia's entire northeast continental margin including the GBR, formed as a result of rifting, uplift and volcanism (Mutter and Karner, 1980; Symonds et al., 1983). The continental margin developed in two main phases: 1) an initial stage of rifting, seafloor spreading, volcanism, graben formation and sedimentary infilling of depressions, which resulted in the formation of a series of troughs and plateaus; and 2) continent separation and margin subsidence, which led to shelf sedimentation and progradation, and ultimately reef development. The Australian plate began separating from Antarctica in the late Jurassic and accelerated in the middle Cenozoic. This northward movement continues today at a rate of 6-7 cm/yr (Veveers, 2000).

The present morphology and structure of the margin has been shaped by continental break-up and rifting in the Late Cretaceous (80 Ma) to Early Tertiary (56 Ma) (Davies et al., 1989; 1993). After its separation from Antarctica, the northward-migrating Australian plate underwent further rifting, subsidence, collision and sea-level fluctuations (Davies et al., 1989). Rifting associated with the opening of the Coral Sea Basin, produced a series of basement highs that formed large shallow water plateaus, suitable for coral reef growth (Falvey and Mutter, 1981; Mutter and Karner, 1980; Hoply and Davies, 1986). The carbonate platform began to develop on topographic "highs" once the continental shelf moved into the tropics. Original rift structures underlie the northeast continental margin today (Fig. 2.1). For example, the western boundary fault of the rift system and sedimentary rift basins such as the Queensland Trough lie beneath the present mid- to outer-shelf (Mutter and Karner, 1980; Davies et al., 1989; Dunbar et al., 2000).

Today the carbonate platform sequence is characterised by a tropical carbonate wedge that thins and becomes younger in the south and also overlies temperate and subtropical facies (Davies et al., 1989). A major part of the evolution of the GBR shelf took place in several phases during the Tertiary (64 to 1.81 Ma). The initiation of reef growth first occurred in northern parts of the continental shelf (Symonds, et al., 1983). Four episodes of reef growth have been recognised by Davies et al. (1989) and occur during the early Middle Miocene (16.4 Ma), the Middle to Late Miocene (~11.2 Ma), the Plio-Pleistocene (3.6-1.8 Ma) and the Quaternary (1.8-0.01 Ma). The evolutionary platform sequence shows that throughout the Eocene and Oligocene sedimentation along the continental margin was subtropical carbonate in the north, and temperate clastic-carbonate in the south. The first reefs on the GBR and nearby Queensland and Marion Plateaus probably formed on red algal bioherms in the Late Oligocene and Early Miocene, which was a result of continued northward drift into topical areas and increased water temperatures. In the Late Miocene, subsidence led to terrigenous-dominated

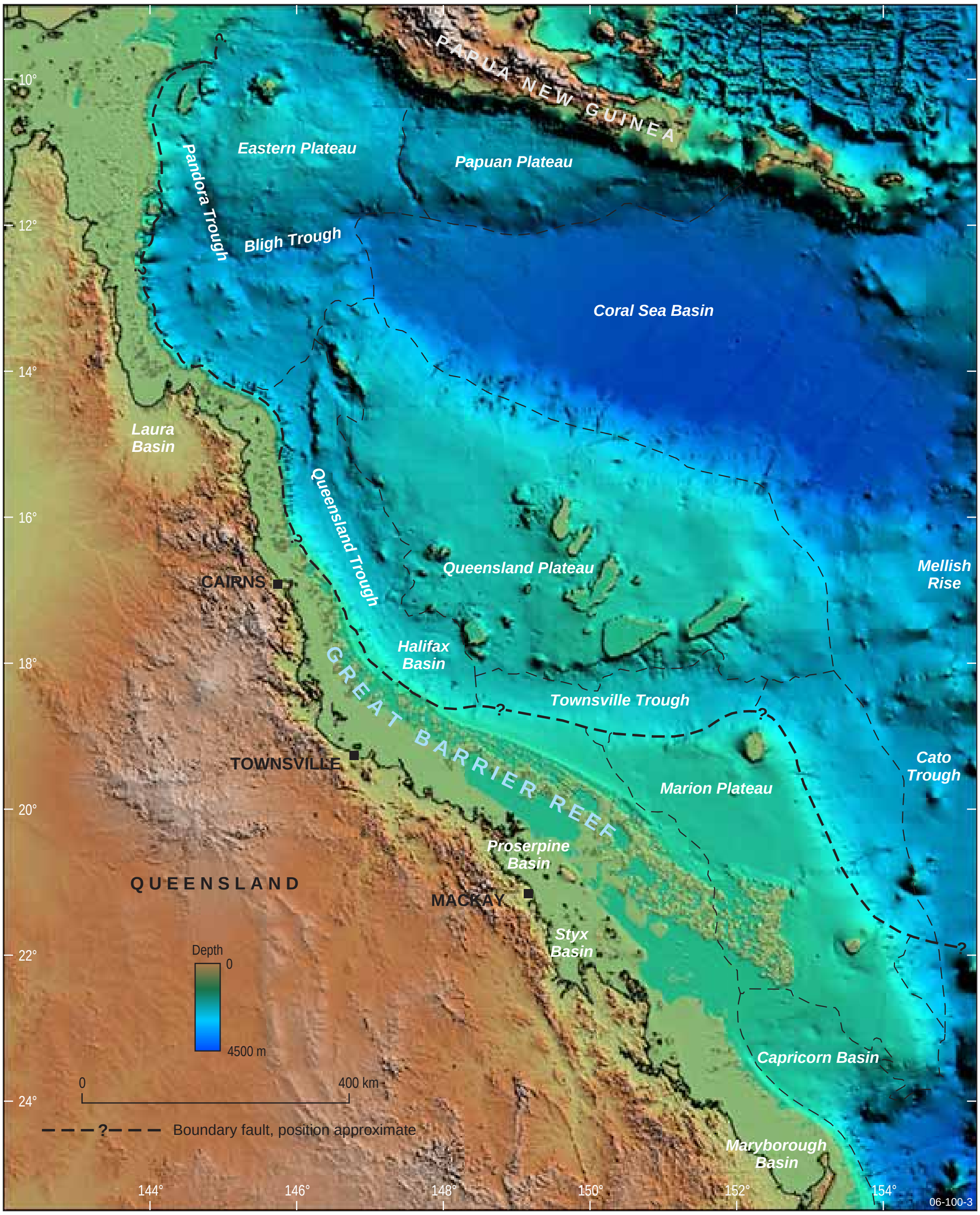

Figure 2.1. Australia's north east continental margin is dominated by major tectonic features including the Queensland Continental Shelf, the Queensland and Marion Plateaus; and the Coral Sea Basin, which is bounded to the north by the Papuan and Eastern Plateaus, and to the east by the Mellish and Louisidale Plateaus. An approximate location of the rift fault which formed during continental margin development is also shown.

sedimentation or exposure in the central GBR, and then in the Pliocene, further subsidence buried the northern reefs (Davies et al., 1989).

Construction of the carbonate platform was probably controlled by fluctuating sea surface temperatures (SST). The main construction phase occurred during the Late Oligocene to Pleistocene (23.8-2 Ma), when average SST's ranged between 20-25°C (Isern

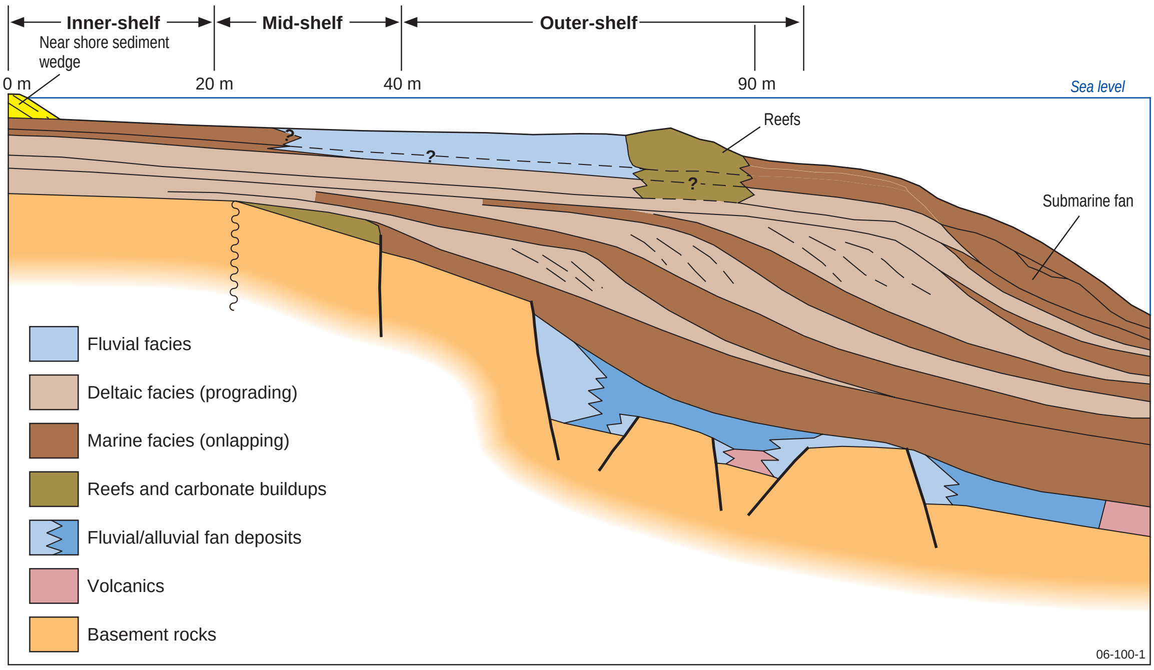

Figure 2.2. Schematic diagram of the continental shelf stratigraphy for the central Great Barrier Reef, and conceptual representation of the tectonic evolution of the north east Australian margin; from initial basement rifting and uplift during the Late Cretaceous / Paleocene, volcanism and alluvial infilling; then later phases of marine transgressions (onlap) and regressions (shelf progradation) that led to outbuilding of the continental shelf; and finally, the Pleistocene marked the onset of periodic reef growth on the shelf edge, which continues to Recent times (modified from Symonds et al., 1983).

et al., 1996). Platform construction resulted in oceanward progradation of the shelf (Fig. 2.2). Northeast Australia has experienced alternating wet/dry and cool/wet conditions on interdecadal timescales (Calvo et al., 2007), which would have controlled carbonate platform development. Sr/Ca ratios obtained from *Porites* coral in the central GBR indicate that cold SST's during the last glacial maximum prevented reef growth in the tropics (Marshall and McCulloch, 2002). This climatic variability is reflected in the stratigraphy of the carbonate platform sequence, which is comprised of interdigitating siliciclastic (terrigenous) and carbonate (marine) sediments. This sequence comprises two main facies types, which include: 1) a lower sub-reefal sedimentary facies, overlain by; 2) a dominantly reefal facies. The upper reef facies is comprised of repeated cycles of transgressional cool water coralline-dominated carbonates, topped by shallow water high-stand coral reefs (Coventry et al., 1980; Davies and Peerdeman, 1998).

2.1.2. Late Quaternary History

Throughout the GBR province, the initiation and growth of modern Holocene reefs on the Queensland shelf had probably commenced by 8,000 BP (i.e. northern GBR), hence the age of the modern GBR is ~7,000 ka (Hopley et al., 1984; Davies et al., 1985; Woodroffe et al., 2000). However, several interpretations for the initiation of the GBR and variations in age from north to south have been proposed (Carter and Johnson, 1986; Hopley and Davies, 1986; Alexander et al., 2001). Reef facies indicate that initial reef growth probably lagged behind sea level rise, but after initial colonization vertical growth was able to catch up with sea level, which had stabilised at its present height by 6,500 BP (Davies and Hopley, 1983; Davies et al., 1985). Reef facies at Redbill Reef in the central GBR, are characterised

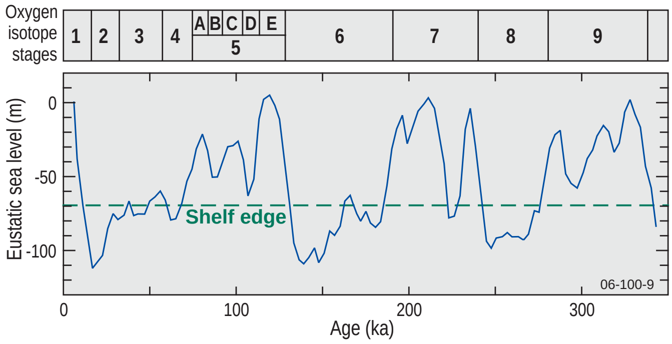

Figure 2.3. Eustatic sea level curve for the north Queensland shelf over the last 350 ky, relative to the central GBR (modified from Dunbar et al., 2000).

by a lower dominantly detrital section, which recorded rapid accumulation rates and an upper framework unit with average rates of accretion (e.g. Davies and Hopley, 1983) (Hopley et al., 1984). Overall, the Holocene section is of variable thickness, and at Redbill Reef Holocene reef facies obtain a thickness of ~12-18 m.

Modern reef growth is mostly established on a foundation of Pleistocene reefs, which formed an 'antecedent platform' characterised by higher relief than the surrounding seabed (Hopley et al., 1978; Johnson et al., 1982; Hopley et al., 1984; Woodroffe et al., 2000). These Pleistocene foundations occur between ~10 m to >20 m beneath the surface of the modern reef flat (Davies and Hopley, 1983; Hopley et al., 1984). The pre-Holocene surface is erosional, with an irregular to incised morphology, reflecting subaerial exposure during the last glacial period (Johnson et al., 1982; Marshall and Davies, 1984).

Most of the available evidence suggests that reef development on the GBR coincided with changes in oceanic circulation which led to a drier and more variable climate and an increase in water temperatures (Davies et al., 1991, Davies and Peerdeman, 1998; Kershaw et al., 2003). Higher, stable sea levels and warm ocean surface temperatures were observed globally, and are considered to mark the onset of prolific reef growth in other parts of the world (Stirling et al., 1998). Such changes in oceanographic circulation led to a gradual change from temperate to tropical shallow water biota on the continental shelf (Davies, 1992). The nearby Queensland Plateau contains the regions oldest surviving reefs (~15 Ma old), which may have provided coral larvae that initially colonised the Queensland shelf (Davies et al., 1991; Davies, 1992; Davies and McKenzie, 1993).

Not long after the establishment of reefs at the shelf edge, between 500-300 ka a large mixed carbonate-siliciclastic province developed in the extensive, shallow water shelf lagoon (Davies and Peerdeman, 1998; Dunbar et al., 2000). Over the last 350 kyr the Queensland continental shelf has been emergent for approximately 50% of the time. Sea level oscillations produced prolonged periods of shelf emergence interspersed with shorter phases of submergence (Dunbar et al., 2000). In the Late Quaternary, the GBR shelf underwent episodic changes in regional sea level, which was characterised by rapid rises, stillstands and gradual, stepped sea level falls (Fig. 2.3) (Chappell, 1994; Larcombe et al., 1995; Larcombe and Carter, 1998). Since 500 ka these eustatic fluctuations have controlled regional sedimentation styles on the shelf and variation in the production (i.e. volume) and distribution of carbonate and siliciclastic material (Dunbar et al., 2000; Dunbar and Dickens, 2003a). Such sea level changes have also been observed at this time

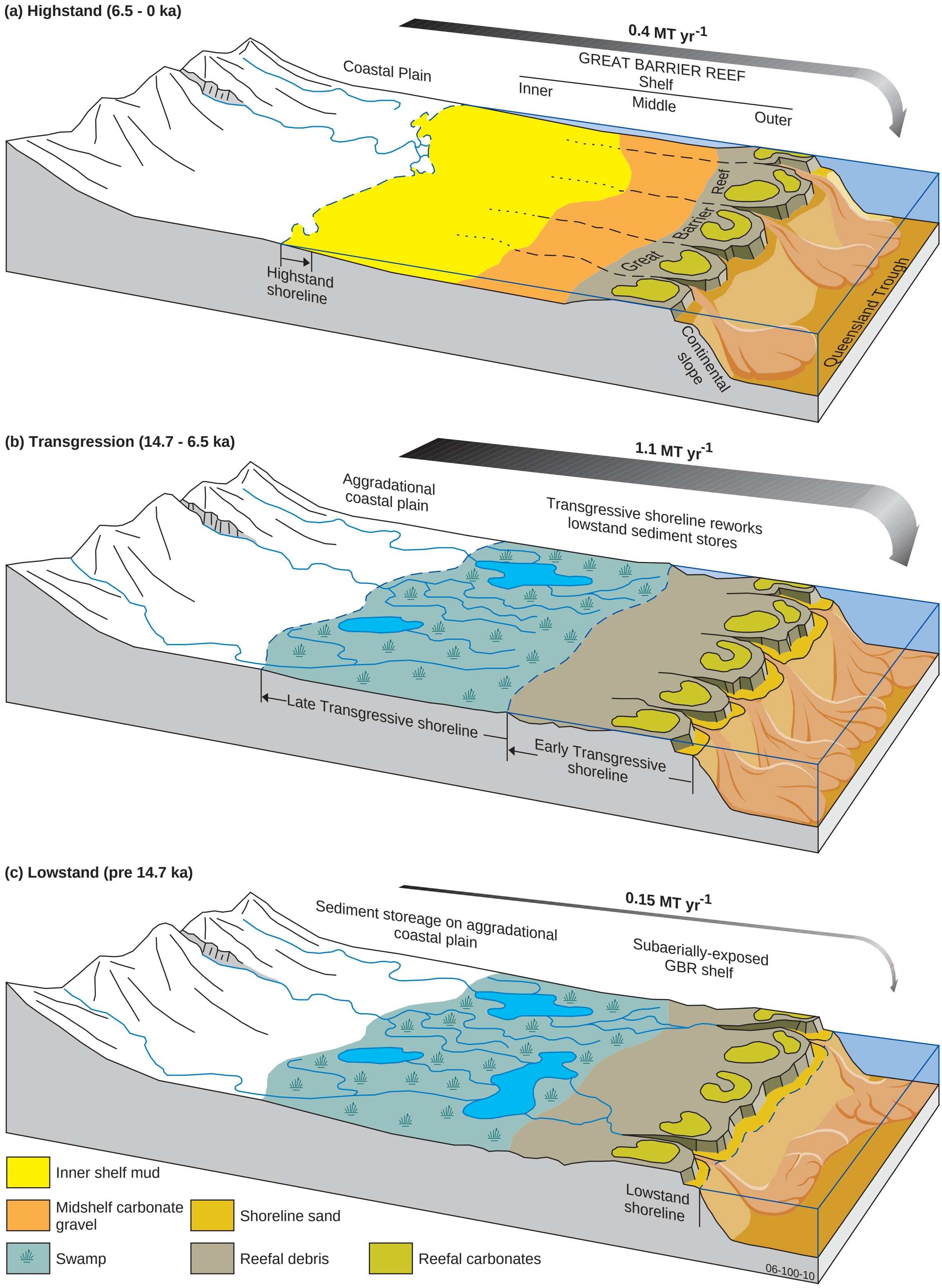

Figure 2.4. Model of shelf depositional environments and morphology coinciding with sea level changes on the Queensland continental shelf over the past 15 ka (modified from Dunbar et al., 2000). Diagram shows the changing shelf environments and movement/behaviour of siliciclastic sediments during highstand (a), transgression (b), and lowstand (c) and the corresponding amount of siliciclastic sediments transported off the shelf during each stage.

on other carbonate systems world wide (e.g. Maldives) (Aubert and Droxler, 1996).

At times of low sea level, the exposed GBR shelf formed a broad coastal plain upon which river sediments aggraded (Fig. 2.4) (Woolfe et al., 1998; Page et al., 2003). Studies of late-Quaternary deep-sea sediments in the Queensland Trough (Dunbar et al., 2000; Page et al., 2003) indicate that during the lowstand terrigenous material is stored on the low-gradient shelf, with very little siliciclastic sediment transported to the deep sea, which is contrary to traditional sequence stratigraphic models. When water levels were 100 m lower than present, the shore line was located beyond the shelf break, and the present reefs formed karstified hills on the outer shelf (Dunbar and Dickens, 2003a). During early transgression, large amounts of siliciclastic sediments stored on the shelf were transported off the shelf by shoreline reworking (Fig.2.4). As the shoreline moved landward and transgressed the low-gradient shelf the present reefs formed 'islands'. Significant amounts of longshore transport occurred as a result of a linear shoreline, which increased the amount of terrigenous material transported off the shelf (Harris et al., 1990). Eventually, the reworking of stored terrigenous sediments on the shelf ceased as the shoreline moved further landward, and water depths increased on the mid-shelf. During the present highstand, terrigenous material, including modern inputs, is trapped against the coast where it accumulates mainly in north-facing embayments (Woolfe and Larcombe, 1998). Overall, the Queensland shelf represents a mixed carbonate-siliciclastic system, which behaves differently to pure carbonate systems (e.g. Read, 1985).

2.2. REGIONAL GEOMORPHOLOGY

Maxwell (1968) initially outlined broad-scale provinces on the continental shelf based on their bathymetric character. The regional geomorphology of the northeast margin is described in detail by Harris et al. (2005), which provides an extensive summary of the main geomorphic features in the region, and area calculations of each distinct geomorphic unit (Table 2.1). Hopley (1982) describes the shelf geomorphology, with an emphasis on the reefs, their distribution, type, morphology and formation.

The northeast continental margin is dominated by a partially rimmed shelf of north-south trending reefs that form the extensive GBR. The shelf bathymetry can be highly complex adjacent to coral reefs, submerged shoals, banks and plateaus. It is dominated in area by a large sheltered lagoon, which contains extensive non-reefal seabed areas and mid-shelf reefs. The reef complex is dissected by inter-reef channels which form pathways for strong tidal currents and exchange of oceanic water with lagoon waters.

The continental shelf extends along the margin for >2,000 km and occurs over an area of ~270,000 km^2 (Belperio and Searle, 1988). The shelf trends in a northwest to southeast direction, from Torres Strait in the north to Fraser Island in the south (Fig. 1.1) (Hopley, 1982; Davies et al., 1991). The northeast continental margin is relatively wide in places and extends for >600 km from the coast to the abyssal plain (Mutter and Karner, 1980). On the outer shelf, the GBR forms a discontinuous chain 2,600 km long that contains approximately 2,500 individual reefs, from 10°S to 25°S (Hopley, 1982). The GBR has a minimum width of <25 km at Cape Melville, in the area of 14°S and reaches a maximum of ~350 km off Cape Townshend, in the area of 22°S (Fig. 2.5) (Hopley, 1982; Maxwell, 1968). Together, the continental shelf and GBR form the most extensive geomorphic feature on the Australian continental shelf (Harris et al., 2005).

Table 2.1. The area of geomorphic features within the Great Barrier Reef Marine Park (from Harris et al., 2005).

Geomorphic Features	*†Kilometre^2*	*Percent*
Apron/fan	50	<1
Bank/shoals	3,270	1
Basin	10,950	3
Canyon	2,270	1
Continental-rise	420	<1
Deep/hole/valley	11,370	3
Knoll/abyssal-hills/hills/mountains/peak	70	<1
Pinnacle	170	<1
Plateau	44,240	13
Reef	19,500	6
Ridge	70	<1
Saddle	6,650	2
Shelf	137,910	40
Slope	78,270	23
Terrace	13,870	4
Tidal-sandwave/sand-bank	550	<1
Trench/trough	14,550	4
**Total:*	345,190	100

†Rounded to the nearest 10
*Sum of raw km's; includes areas of land 1,020 km^2 (<1%)

Overall, the continental shelf is generally shallow (0-90 m), with water depths averaging 40 m in the lagoon. Coral reef growth occurs in the shallow waters of the lagoon, which abruptly deepens immediately east of the barrier reefs. The shelf has a gradient of between <1-4 m km^{-1} from the coast to the outer shelf, and gradually deepens from north to south (Hopley, 1982). Water depths in the Torres Strait are <15 m and increase to ~30 m in Curtis and Capricorn Channels. Reefs in the Capricorn-Bunker Group rise from water depths of between 55 and 60 m (Hopley, 1982). The shelf break generally occurs at 70-90 m water depth, and gradually deepens to >110 m towards the south.

Maxwell (1968) identified three broad regions of common bathymetry and dissimilar reef distributions on the continental shelf. These are: 1) the 'Northern Region', between 9°S and 16°S, which is characterised by a narrow shelf only 24 km wide at Cape Melville, and an almost continuous chain of shelf-edge ribbon reefs; 2) the 'Central Region', between 16°S and 20°S, which is wider than the northern shelf, with a more sparse distribution of shelf-edge reefs and extensive platform reefs on other parts of the shelf; and 3) the 'Southern Region', between 20°S and 24°S, which is the widest section of shelf where it attains 300 km near the Swain Reefs, and has complex deltaic reefs at the shelf-edge forming the Pompey Group and Swains Reefs (Maxwell, 1968).

The broad shelf lagoon covers an area of 325,590 km^2. In general, the seabed topography of the lagoon varies from wide, broadly shelf-parallel horizontal plains, to low ridges and small escarpments (Fig. 2.6). The seabed varies in complexity from smooth and featureless with sparse reef edifices on the inner and middle shelves, to a complex framework of near-vertical reef edifices with adjoining talus slopes, interspersed with deep inter-reef passages on the outer shelf (Maxwell and Swinchatt, 1970). It generally has a gentle gradient to 40 m water depth and then steepens slightly to 70 m towards the shelf edge (Hopley, 1982). The shelf lagoon covers a relatively extensive area compared to the reefs, which merely occupy 19,500 km^2 of the Marine Park (Table 2.1).

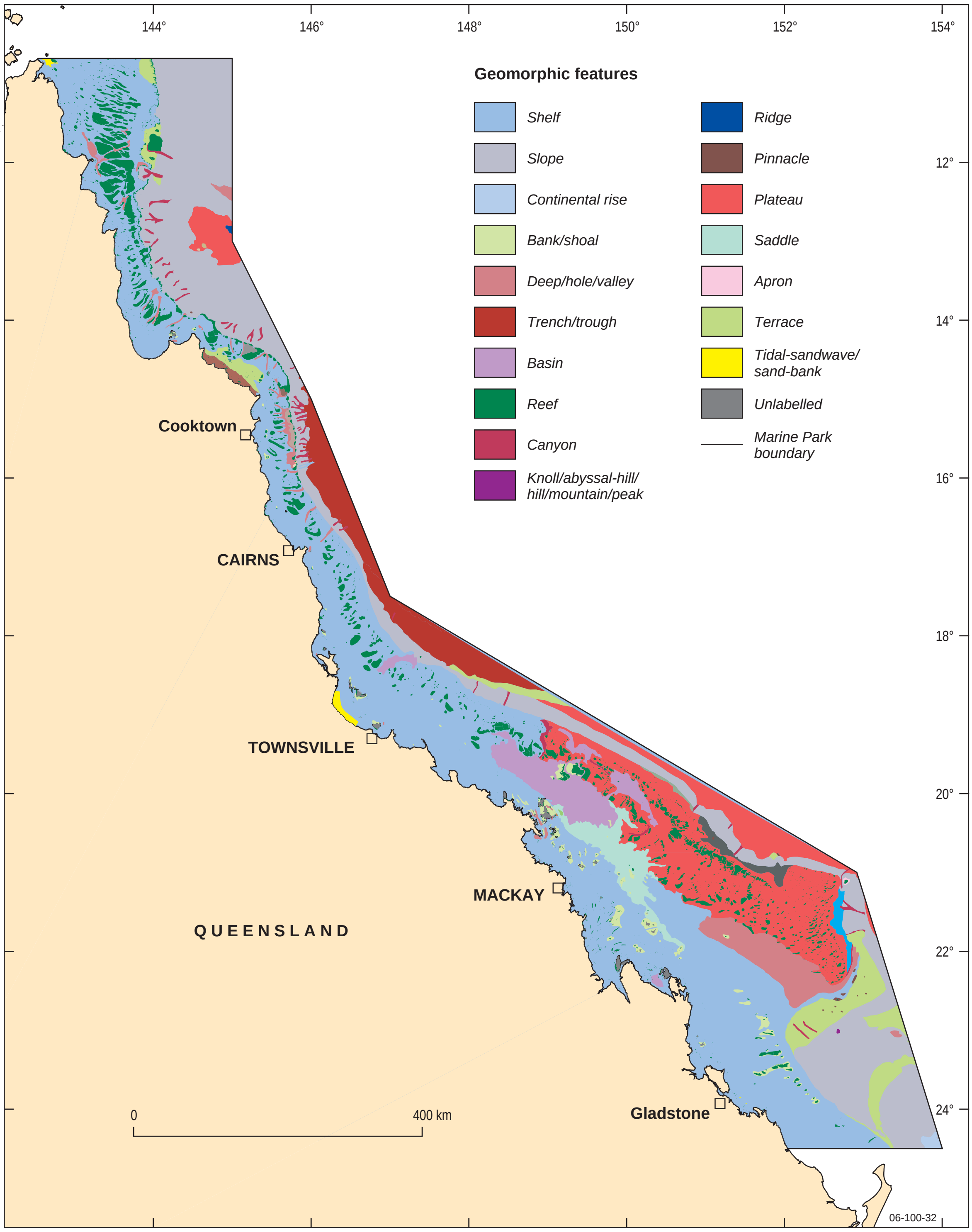

Figure 2.5. Geomorphic features of the north east margin of Australia, illustrating the main geomorphic units on the continental shelf and slope within the Marine Park (from Harris et al., 2003).

The inner shelf region occurs from the coast to 20 m water depth and is <60 km wide (Belperio, 1983a). It is generally characterised by a uniform gentle gradient of ~<1 m^{-1} km, smooth seabed and a small number of coral reefs (Carter et al., 1993). Generally, the inner shelf contains continental high islands (some with extensive fringing reefs), sparse inner shelf reefs, sand ridges, bars, banks, rock masses, scour channels, estuarine and deltaic features (Maxwell, 1968). The nearshore zone (0-9 m water depth; Maxwell,

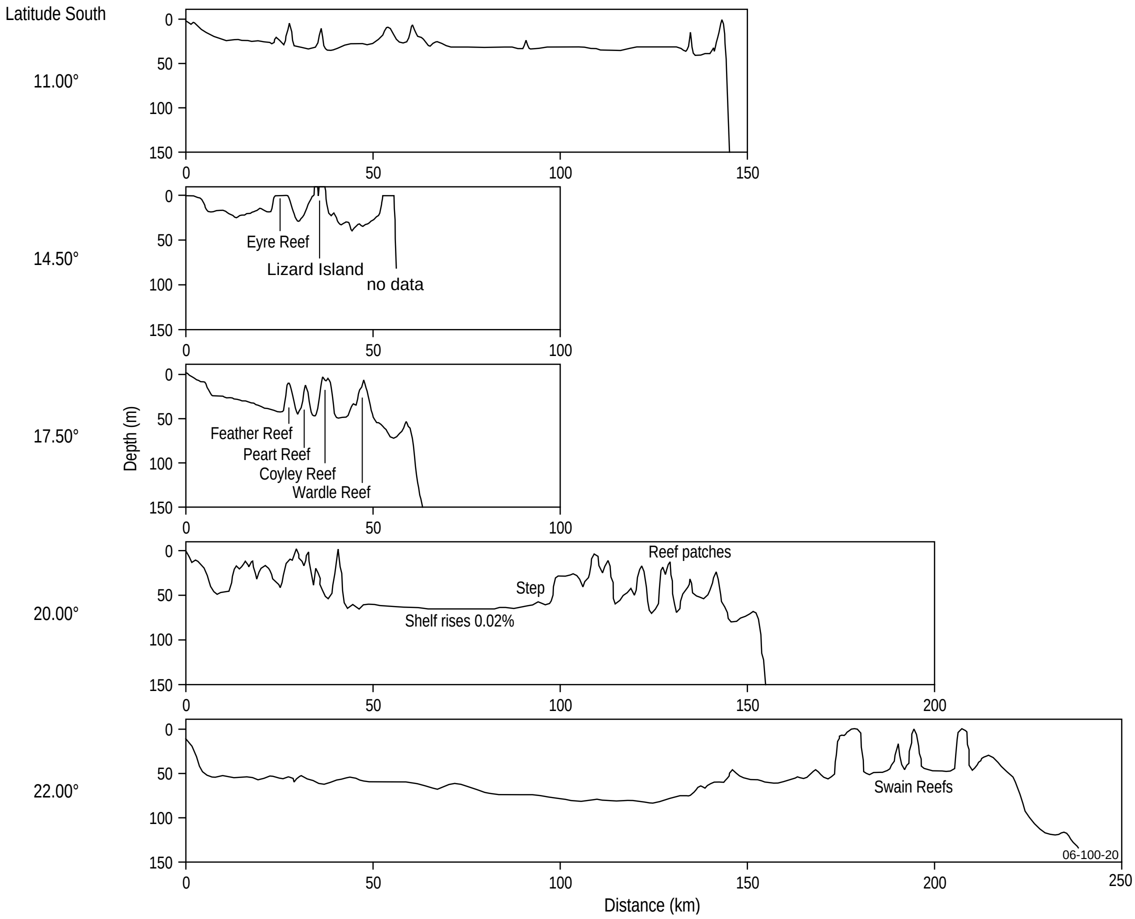

Figure 2.6. Examples of cross-shelf bathymetric profiles from; (a) Torres Strait region, showing broad northern shelf and steep continental slope, (b) Lizard island region showing deepening shelf beyond the Island, overall narrow continental shelf and steep slope, (c) Feather and Wardle reefs showing the complex bottom topography that occurs between the reefs and shelf edge, (d) Hamilton Island region showing the flat middle shelf region and the complex bathymetry of the inner and outer shelf, and (e) Swain Reefs region showing the broad continental shelf, reef topography and gentle continental slope (modified from Lewis, 2001).

1968) is active and more topographically variable due to the influence of high energy wind- and wave-dominated processes. For example, in Halifax Bay large ~8 km long field of transverse dunes has developed in 8 to 12 m water depth, and are orientated almost perpendicular to the shoreline (Maxwell, 1968; Larcombe and Carter, 2004). North-facing embayments such as Cleveland Bay contain a sediment fill, which forms part of the shore parallel sediment wedge (Fig 2.7). The sediment wedge is thicker in north-facing embayments, and in Cleveland Bay it is terraced and characterised by a short steep fore-slope at 10 m water depth that merges with the gentle gradient of the shelf surface near 20 m water depth (Carter et al., 1993).

The middle shelf is up to 55 km wide, occurring in water depths of 20 m to 40 m (Belperio, 1983a). This part of the shelf is relatively featureless and flat to gently sloping, with local dune fields. Other environments include; low wooded islands, and sparse fringing, small platform and crescentric coral reefs (Flood and Orme, 1988). Patch reefs and continental islands surrounded by fringing coral reefs produce a complex geomorphology of near-vertical slopes adjacent to relatively flat seabed areas (Heap et al., 2001). Large reefs rise sharply from the seabed off Princess Charlotte Bay and elsewhere in 30-40 m water depth (Hopley, 1982). Local sandwaves and longitudinal dune fields

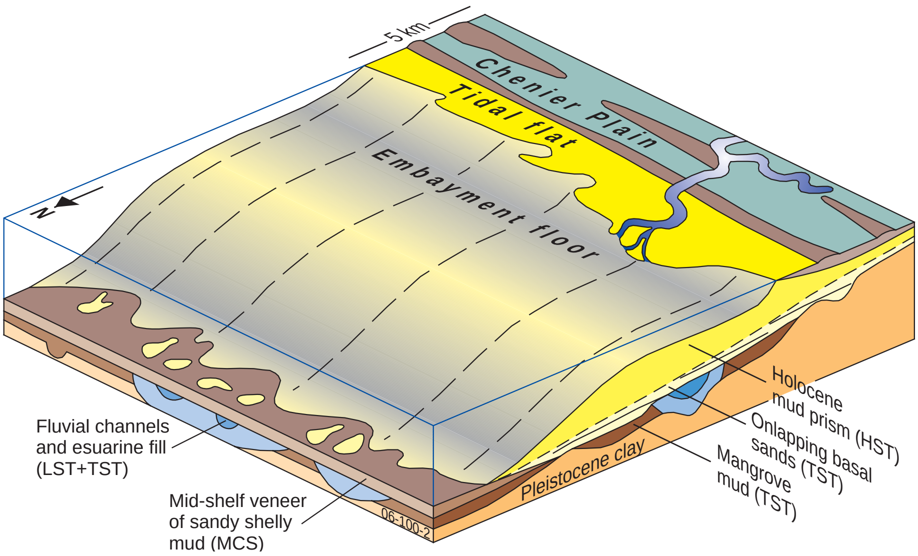

Figure 2.7. Idealised model of the inner shelf seabed in Cleveland Bay (modified from Larcombe and Carter, 1998). It shows the morphology of the shore-connected terrigenous sediment wedge and ocean ward dipping fore-slope separating it from the flat plain of the remaining shelf.

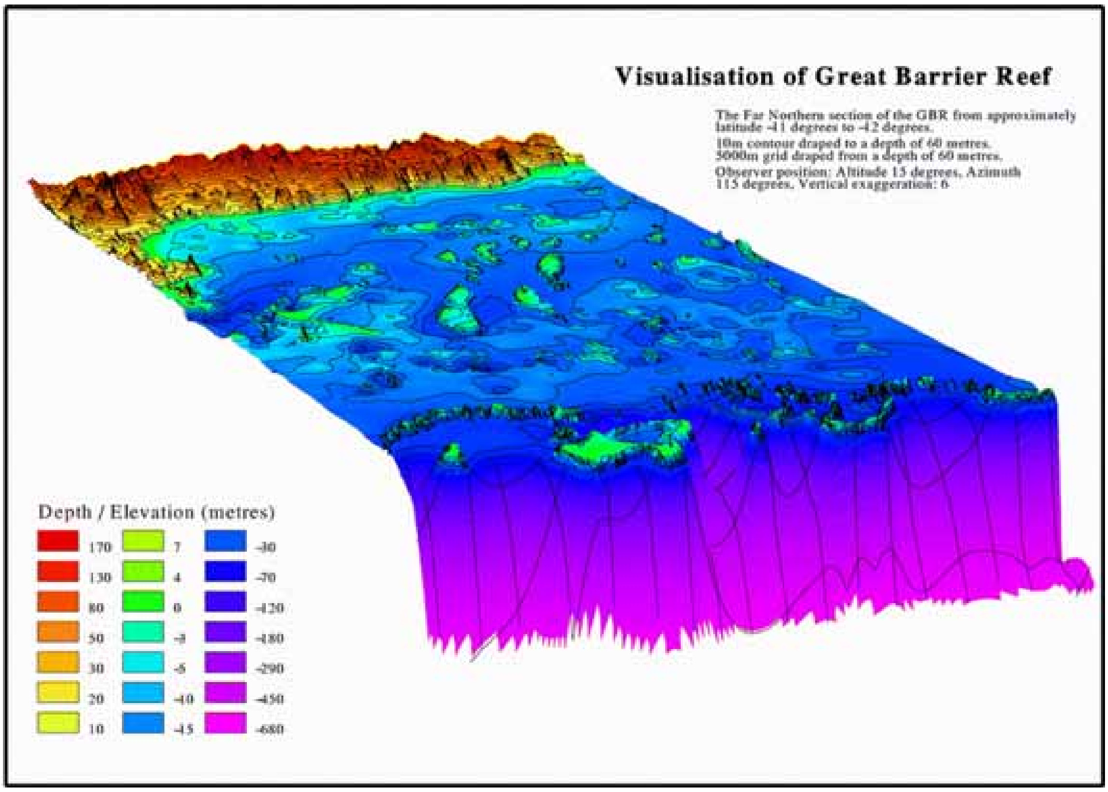

Figure 2.8. Bathymetry of the shelf edge reefs and shelf seabed in the vicinity of Princess Charlotte Bay, far northern GBR (from Lewis, 2001).

form irregular seabed regions on parts of the middle shelf (Johnson et al., 1986). Relatively flat seabed comprises areas of old hard substrate and is locally devoid of sediments. Such hard substrates may have been exposed by strong currents and cyclones (Larcombe and Carter, 2004).

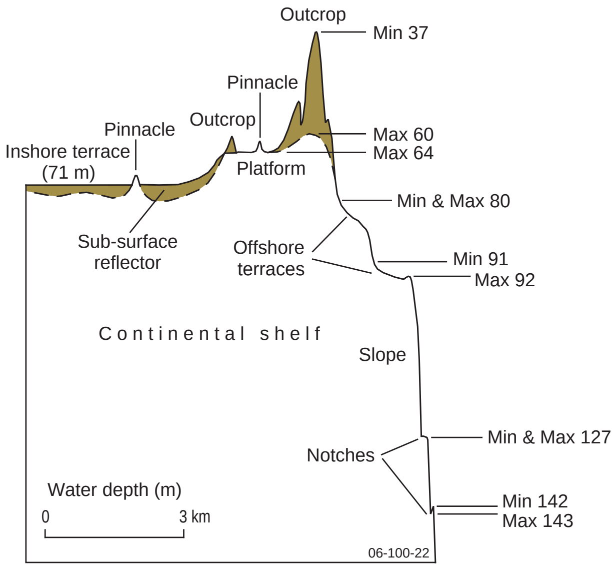

Figure 2.9. Schematic profile of the shelf edge and geomorphology of reefs and related water depths (modified from Harris and Davies, 1989).

Widespread reef growth begins at approximately 35 m water depth on the middle shelf, and extends to >60 m on the outer shelf/shelf edge (Hopley, 1982). On the outer shelf and shelf edge reefs form a discontinuous chain, about 10 km wide, on the seaward side of the lagoon (Fig. 2.8). The outer reef comprises a discontinuous barrier of areas of high and low reef density. The reefs, together with localised reef shoals and marginal seaward-sloping terraces form a partially rimmed continental shelf that impedes wave action, producing an extensive protected lagoon (Belperio and Searle, 1988).

Regions of high reef density form a complex bathymetry characterised by vertical, high relief pinnacles interspersed with deep inter-reef channels. Reefs form steep-sided coral edifices that rise abruptly from the seabed, and usually have a gentle leeward talus slope and steep windward edge (Fig. 2.9). In all regions, reefs vary in shape from kidney-shaped with a lagoon (e.g. Bowden Reef) to flat platforms with no lagoon. The reef surface can be rugose from centimetre scale irregularities to heavily cemented reef flats comprising prolific coral growth several metres high (Hopely, 1982). Patch reefs in the cental GBR, form numerous near vertical pillars, which are surrounded by talus aprons and areas of flat seabed (Harris et al., 1990). Reefs on the outer shelf commonly display variable morphologies, and include ribbon, linear and cuspate forms, which are generally oriented north-south. Reefs in the Torres Strait display an east to west orientation. Individual linear and ribbon reefs vary in length from 3 to 25 km and are 300 to 450 m wide, separated by narrow passages typically 40 m deep (Flood and Orme, 1988). The ribbon reefs occur as far south as Hinchinbrook Island (Hopley, 1982). The nature of the pre-Holocene surface and the shape of existing topographic and structural highs influence the range of reef growth forms (Harvey et al., 1978; Hopley, 1982; Marshall and Davies, 1984).

Other seabed features within and adjacent to the outer reefs make this a region of highly complex geomorphology. Some local non-emergent reefs and reefal shoals occur within the main reef complex. These features have distinct morphologies comprising fore-reef and lagoon, and are probably drowned reefs (Hopley, 1982; Lewis, 2001). Scattered rocky outcrops occur towards the shelf edge in ~100 m water depth offshore from Palm Passage (Scoffin and Tudhope, 1985). These features are generally 1-10 m in diameter and commonly have rugose surfaces with a sharp, irregular relief of 0.5-2 m. Such rocky outcrops may be former reefs or the partially buried erosional remnants of shelf edge limestones (Scoffin and Tudhope, 1985).

Inter-reefal areas occupy extensive parts of the GBR shelf, and include broad inter-reef plains and narrow channels. Inter-reef plains occupy extensive seabed areas and surround zones of reef growth (Maiklem, 1966). The inter-reef plains are generally smoothly sloping with scattered protruding coral edifices. In the Capricorn region, these seabed areas have a gently undulating morphology of smooth sandy seabed, interspersed with numerous 'spikes' considered to be coral growth (Maiklem, 1966). As the reefs have been the focus of much work over the years, there is a dearth of knowledge about the sedimentary and geomorphic character of these extensive plains (Hopley, 1982).

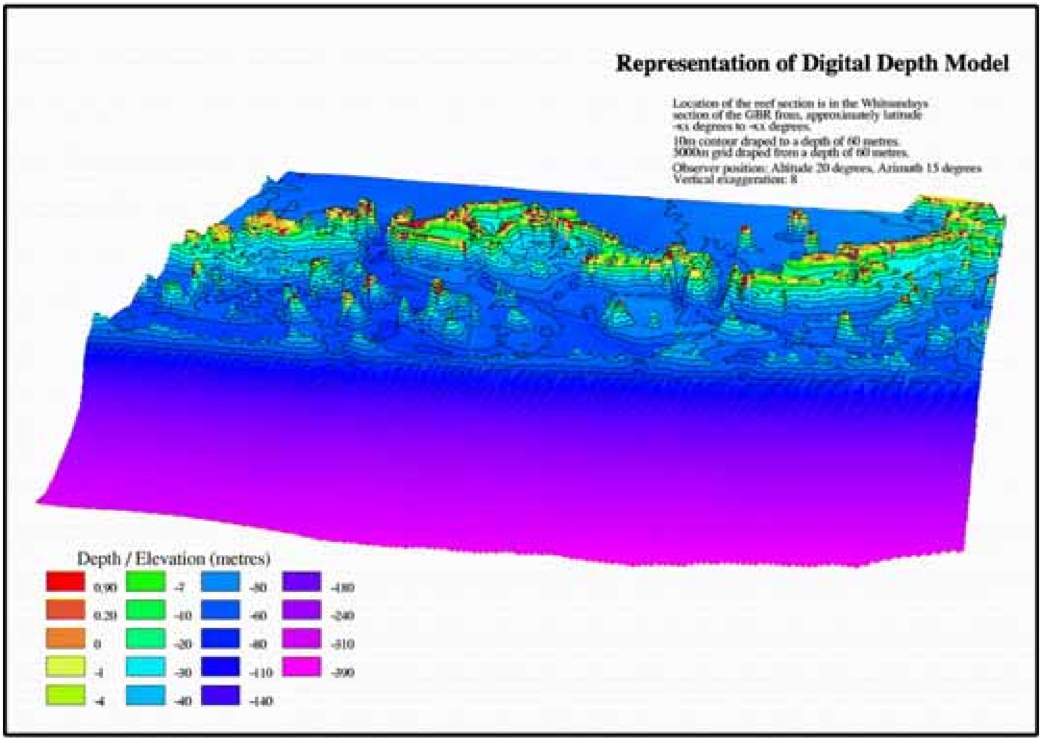

Figure 2.10. Bathymetry of the reefs in the Whitsunday Group, showing the geomorphology of large inter reef passages between the islands and reefs (from Lewis, 2001).

Narrow inter-reef channels separate individual reef edifices, and are major geomorphologic features in the GBR lagoon and barrier reef complex (Harris et al., 2005). Inter-reef channels are bordered by fore-reef slopes which act as channel walls (Maiklem, 1966). They are generally deep and steep-sided and display meandering and dendritic paths similar to the pattern of tributaries on land (Hopley, 1982). Some of these channels are continuous and others are 'blind' and partly or completely blocked by rocky outcrops or reefal shoals (Harris et al., 2005). Channel depths range from ~50 m to >90 m and are generally deeper than the shelf depth of seabed nearby to the reefs (Hopley, 1982). The channel floors may be flat and sediment covered with rare rocky outcrops (Scoffin and Tudhope, 1985). Many of the channel floors have been swept clean and scoured by strong tidal currents. Inter-reef channels in the Capricorn Group contain coarse sand and gravel lags (Maiklem, 1966). Some of these channels are several hundreds of metres, to tens of kilometres wide. Within large reef complexes such as Pompey Complex, channels extend beyond the limits of the shelf edge reefs and are up to 1 km wide and >90 m deep (Hopley, 1982). The larger inter-reef channels such as Capricorn and Curtis Channels and the Grafton, Palm and Hydrographers Passages, are recognised shipping routes (Torres Pilots, 2001). The larger inter-reef passages may represent major Pleistocene drainage channels that formed during low stand sea level (Johnson et al., 1982).

Halimeda banks can form highly complex areas of undulating seabed. The seabed offshore from Cape Flattery in the northern GBR is one such area where *Halimeda* banks comprise 26% of the total shelf area (between 14°27'S and 15°02'S) and are concentrated on the outer shelf (Orme and Salama, 1988). The algal banks consist of a well developed mounded surface of troughs and hollows with variable relief, which is most prominent in eastern parts of the outer shelf (Fig 2.11). Smaller banks are found in western areas. The high relief tops of these banks can rise to within 25 m of mean sea level. Their variable relief produces significant changes in water depth of 15 m, which can occur over distances of less than 50 m (Orme and Salama, 1988). An extensive blanket of *Halimeda* algae meadows cover their surface, with localised corals occurring in the troughs between banks. At other locations on the shelf edge, extensive *Halimeda* meadows form adjacent to reefs and form banks that rise 10 m to 20 m above the seabed. In the Capricorn region, algal mounds up to 4 m high form an area of rough seabed that extends over an area of 4 km in 80 and 120 m water depth on the shelf edge (Davies et al., 2004). These mounds are made of thick coralline algal boundstone, which has grown on an erosion surface during the Holocene transgression (Davies et al., 2004).

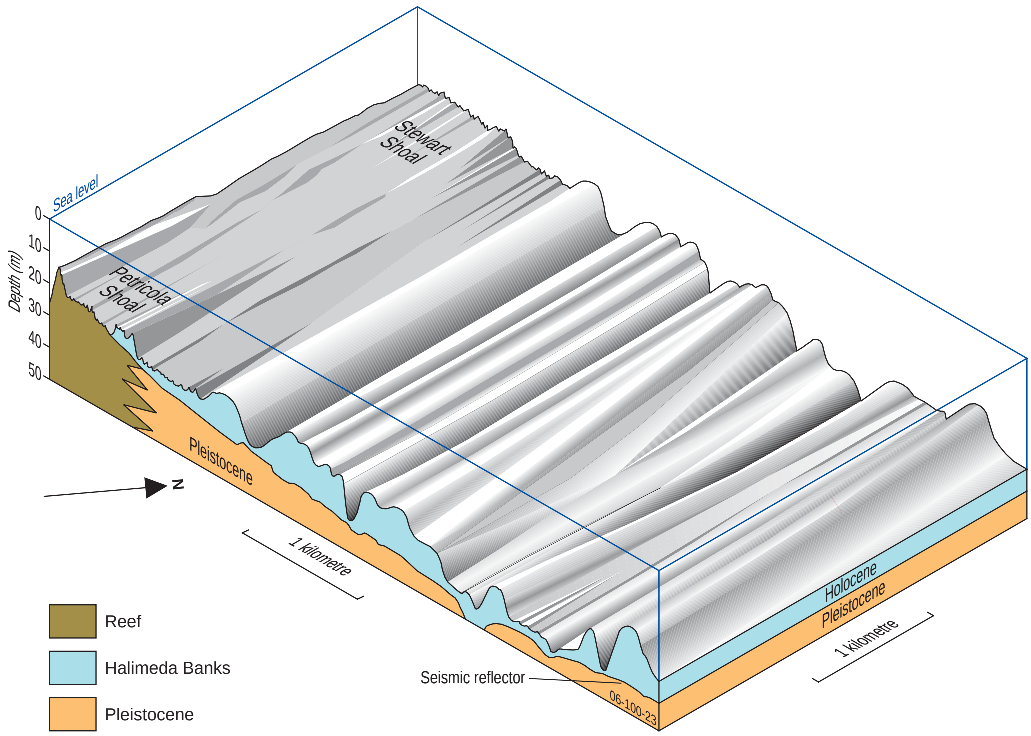

Figure 2.11. Schematic interpretation of the seabed in the northern GBR based on seismic reflection profiles. The area has a complex bathymetry of *Halimeda* Banks that overly the Holocene erosion surface. The banks are laterally continuous, shelf parallel features consisting of high relief mounds, deep troughs and hollows (modified from Orme and Salama, 1988).

The shelf break generally occurs in water depths of 100 m to 200 m along the length of the GBR continental shelf. Beyond this depth, the seabed drops away to reach water depths of >1,000 m located less than 1 km from the shelf edge (Hopley, 1983). The continental slope dips steeply, forming abrupt escarpments on the margins of the northern GBR shelf. The slope decreases offshore from Townsville and then becomes gently dipping in the south adjacent to the Marion Plateau (Hopley, 1982). The upper slope is characterised by numerous submerged reefs, extensive offshore platforms, and small terraces, in water depths of <170 m (Harris and Davies, 1989; Harris et al., 2005). A reefal limestone scarp extends from the shelf edge to >300 m water depth. The upper slope is devoid of extensive canyon systems, however it is incised in the north and south, particularly adjacent to the Ribbon Reefs (Davies et al., 1991).

Offshore from the continental shelf, in the Coral Sea, lie several large submerged platforms, these include the Eastern, Queensland and Marion Plateaus (Fig. 2.12) (Mutter and Karner, 1980). The marginal plateaus are steep sided with a smooth or convex surface and each support modern coral reef growth (Mutter and Karner, 1980). The Marion Plateau forms a deep-water extension of the continental shelf. The Queensland Plateau is the largest marginal plateau (Symonds et al., 1983). It occurs at a depth of 1,100 m and exhibits a smooth to planar surface away from reef areas (Davies et al., 1991). Active reefs occupy ~10-15 % of the plateau surface, which is bounded by linear troughs. Steep-sided reef pinnacles occur in the west and are 1-2 km wide, rising from >1,200 m water depth to within 10 m of the surface (i.e. Osprey Reef) (Davies et al., 1989).

Each of the offshore plateaus are separated by large topographic depressions, which include the Pandora, Bligh, Queensland and Townsville Troughs (Fig. 2.12). The Queensland Trough separates the continental shelf from the Queensland plateau and extends for >550 km, covering an area of 80,000 km^2 (Harris et al., 2005). It occurs in water depths of 1,100 m to 3,000 m and gently deepens in a north-westerly direction (Davies et

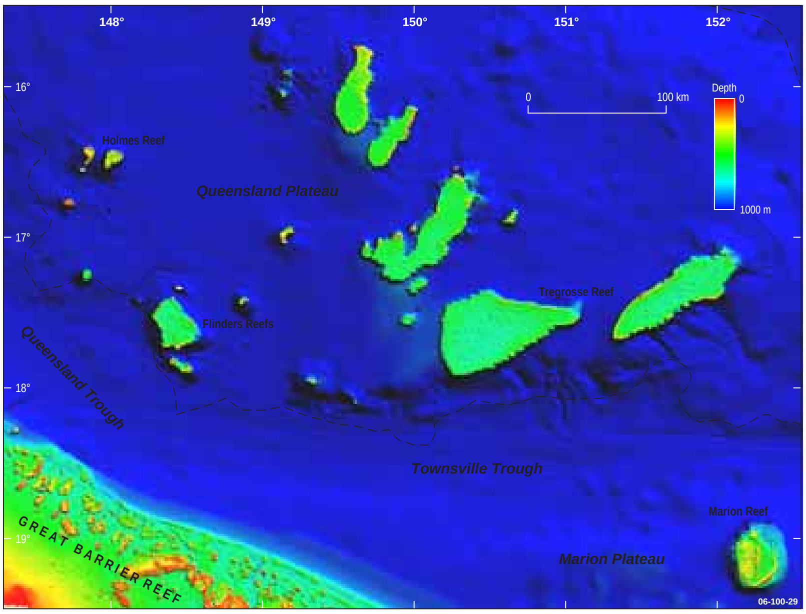

Figure 2.12. The principal bathymetric features of the Queensland Plateau, occurring east of the continental shelf, showing Bougainville Reef, Holmes Reef, Diane Bank, Willis Islets, Corninga Bank, Flinders Reeefs, Tregrosse Reef and Lihou Reefs and Osprey Reef (locations from Davies et al., 1991).

al., 1991). It has an asymmetric profile with exposed bedrock and elongate surface sediment (gravity flow) deposits occur on the floor, parallel to the trough axis (Harris et al., 2005). The Townsville Trough has a symmetrical U-shaped profile and may provide a pathway for sediment from the continental shelf and Queensland Plateau out to the deep ocean floor (Davies et al., 1991).

2.3. OCEANOGRAPHY

The regional geomorphology of the GBR shelf as a rimmed platform significantly affects the physical oceanography of the lagoon. Water circulation and oceanographic processes on the GBR shelf and in the lagoon are influenced by the interaction of several processes including wind-driven currents, regional oceanic circulation, and tides. The seabed topography of the GBR restricts water circulation as regions of high and low reef density within the reef complex form a semi-permeable barrier that controls ocean swells, circulation and currents.

Wolanski (1994) provides a comprehensive synopsis of the physical oceanography of the GBR lagoon, describing the primary hydrodynamic processes affecting biological and physical seabed processes. A summary of the main factors influencing the seabed, such as waves and tides, is provided by Passlow et al. (2005).

2.3.1. Water Circulation

Water circulation over the GBR lagoon and shelf is primarily controlled by the southeast trade winds, large-scale ocean currents, and inflow of water from the Coral Sea (Wolanski, 1994). The southeast trade winds promote the northward movement of lagoonal water, which generates along-shore currents in the GBR lagoon (Lambeck et al., 1998). They are generally constant over the entire GBR and dominate lagoon circulation between May and October. The trade winds overwhelm any south-directed tidal flows and maintain a well mixed water column (Pickard et al., 1977; Wolanski, 1994; Lambeck and Woolfe, 2000; Hemer et al., 2004). The southward movement of the Intertropical and South Pacific Convergence Zones between November and April weaken the pervasive effects of the trade winds. During these months, north and northwest winds are associated with the monsoon season and are weaker and more variable (Maxwell, 1968; Pickard et al., 1977; Wolanski, 1994). This results in alternating northward and southward current movement (Wolanski and Thomson, 1984). In contrast to the trade wind season, water movements are dominated by oceanic and tidal currents with a residual element of southward-directed wind-driven flow. In addition, tropical cyclones are common at this time of year and can generate significant water movement.

The GBR lagoon and shelf water is isolated from the oceanic waters of the Coral Sea by the outer shelf barrier reefs. Waters in the lagoon are generally well mixed and consist of a combination of three main water masses: lagoon water, shelf-break water and Coral Sea surface water (Fig 2.13) (Andrews, 1983). In the absence of wind-driven currents, across- and along-shelf currents in the GBR lagoon are controlled by the interaction of these water masses and regional low-frequency ocean currents in the Coral Sea. The exchange between lagoon water and oceanic water is greatest on the outer shelf, as the westward flowing surface waters of the Coral Sea mix with lagoon water. This exchange occurs principally during the monsoon season (Brinkman et al., 2001). Currents on the outer shelf are influenced by the East Australian Current, which flows southward and can

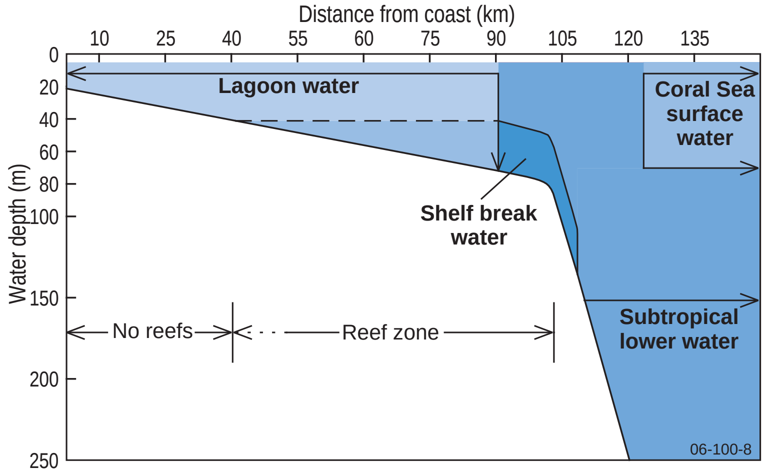

Figure 2.13. Schematic profile showing the 3 individual water masses that effect the central GBR, with distance from the coast (modified from Andrews, 1983). Lagoon/shelf waters occur in water depths of <70 m on the continental shelf; Coral Sea surface water comprises the top 65 m of the water column, shelf break water occurs on the continental slope between 70 m and 200 m. Shelf break water is a mixture of lagoon water and Coral Sea surface water and connects the surface water masses with subtropical lower water, which forms below 200 m (Wolanski, 1994; Andrews, 1983).

attain surface velocities of 1.0 m s^{-1} (Church, 1987). The regional forcing of the East Australian Current also affects mixing between the water masses on the GBR shelf. Vertical salinity and temperature changes can occur in lagoon water as a result of seasonal fluctuations (i.e. high rainfall during monsoons) and up-welling events on the outer shelf (Pickard et al., 1977; Wolanski, 1994).

Tides on the northeast Australian margin and the GBR lagoon are both diurnal and semi-diurnal (Andrews and Furnas, 1986; Wolanski, 1994). The region generally has a tidal range of ~2 m, although locations such as Broad Sound have a tidal range of up to 8.2 m, which significantly enhances current velocities (Cook and Mayo, 1978; Harris et al., 2000). Locally, tidal currents become accelerated between areas of complex bathymetry such as reefs and islands (Church et al., 1985). Velocities of up to 1.5 m $^{-1}$ occur around islands and reefs in the Torres Strait and Capricorn Group, compared with <0.35 m^{-1} on more open (i.e. un-rimmed) parts of the shelf (Fig. 2.14) (Harris et al., 2000). Tidal currents play an important part in mixing of lagoon and oceanic waters (Church et al., 1985). In general, diurnal tidal components have a long-shore (NW-SE) orientation, while the semi-diurnal component is oriented in an across-shelf (W-E) direction (Church et al., 1985). Cross-shelf tidal currents are suppressed by southward-directed long-shore winds and the south easterly trade winds (Woolfe and Larcombe, 1998).

In general, tides flood in a shoreward direction and ebb in an oceanward direction, but tidal streams vary as a result of location. In the northern GBR the semidiurnal tide floods to the south, opposed to the southern GBR where it floods northward (e.g. Nara Inlet; Stewart et al., 2000; Wolanski, 1994). Regions of high and low reef density can control the character of tidal currents, with large spatial variability in tidal phase and magnitude found at different sites. Strong tidal current flows form tidal jets when forced through narrow inter reef passages (Wolanski, 1994). On the outer shelf, tidal currents are oriented cross-shelf and eddies are generated by reefs and other seabed irregularities (Wolanski, 1994). At the shelf edge, the interaction of long-shore currents with topographic irregularities on the seabed is thought to generate large-amplitude internal tides (Wolanski and Pickard, 1983).

2.3.2. Sediment Transport

Sediment transport in the GBR lagoon is influenced by the interaction of the southeast trade winds, nearshore wind-driven currents, storms and cyclone events, fluvial inputs and the morphology of the coast and continental shelf seabed (Orpin et al., 1999). Overall, long-term (>1 year) advective transport in the central GBR is controlled by low frequency wind-generated currents on the shelf and non-residual currents in the reef complex (Wolanski, 1994). Fair weather sediment transport is dominated by resuspension of fine

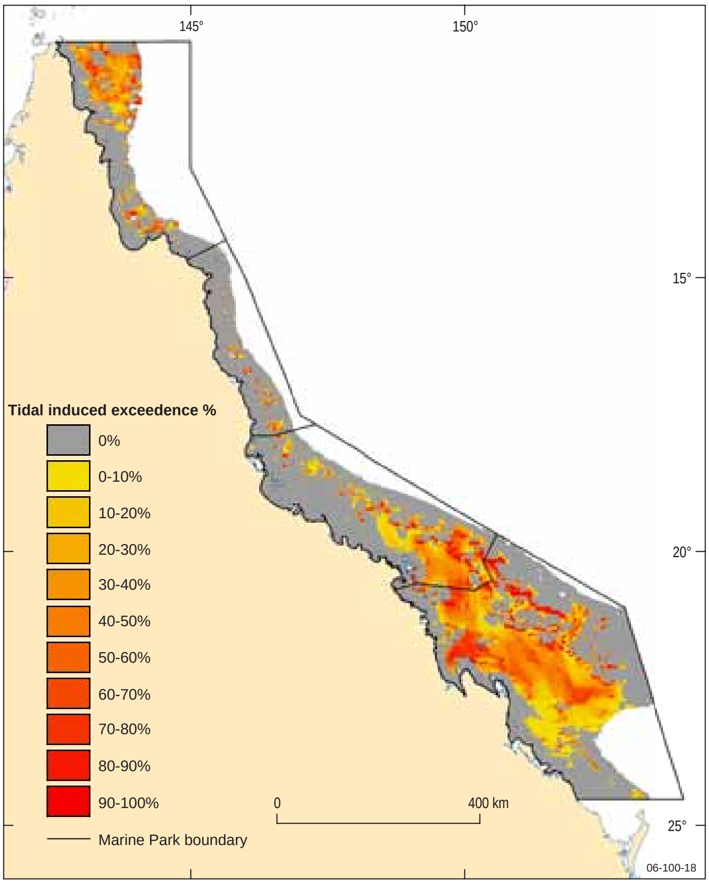

Figure 2.14. GEOMAT Tidal-induced threshold exceedance caused by tidal currents on the GBR shelf (from Passlow et al., 2005). Steady tidal currents with fast water flow velocities exert shear stress on the seabed that is capable of mobilising bed sediments. Some of these high flow velocity regions are found within the GBR, and the threshold exceedance is an estimate of the percentage of time tidal currents flow at high velocity. In Broad Sound and offshore from Rockhampton tidal-induced exceedance is considerable, at >10%.

material (mud) by near-bed currents generated by the southeast trade winds and overall northward littoral drift (Larcombe and Carter, 2004).

The most important mechanism of sediment resuspension (i.e. erosion and entrainment) in the GBR is wave-induced bed stress, which includes short-period wind waves, longer period swell waves and tidal and wind-driven currents (Orpin et al., 1999). A regionalisation of the continental shelf based on estimates of wave and tidal exceedance shows that the GBR shelf is dominated by waves, with localised tide dominated areas

(Porter-Smith et al., 2004). When the orbital motion of surface (ocean swell) waves is sufficient to mobilise sediments grains, suspended-load transport may occur (Fig. 2.15). Swell waves are generally most active in shallow waters near reefs and the coast. In these areas, sediments are mobilised by waves for >1% of the time over 5 years (Passlow et al., 2005). Generally, tidal currents are weak across most of the shelf. However, sediment transport on the outer shelf is controlled by strong tidal currents, producing a current-swept environment (Maxwell, 1968; Flood and Orme, 1988). Tidal currents mobilise surface sediments on inter-reef areas and local acceleration through narrow inter-reef passages sweep the floor clean of sediments (Fig. 2.14) (Passlow et al., 2005).

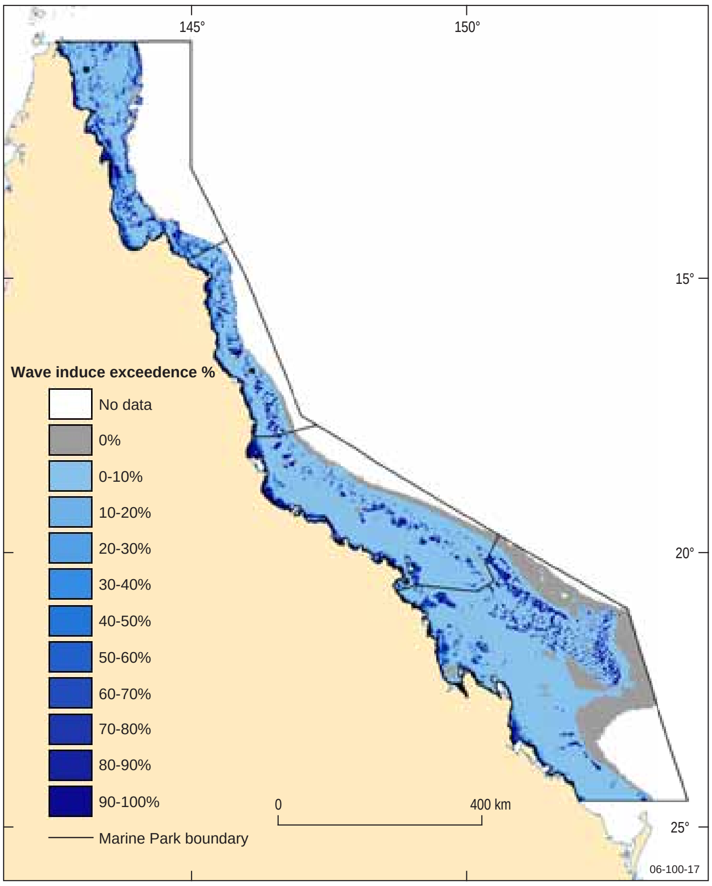

Figure 2.15. GEOMAT Wave-induced threshold exceedance due to swell waves on the GBR shelf (from Passlow et al., 2005). Surface ocean waves and other wind-generated waves are capable of mobilising sediments by orbital water motions. In shallow waters, such as occurs above reef pinnacles, these orbital current motions are felt at the seabed. Wave-induced threshold exceedance is an estimation of the percentage of time that surface waves are capable of mobilising seabed sediments.

Sediment transport is more prominent on the inner and outer shelves, than the middle shelf, due to persistent wind and swell waves in the shallow waters of coastal areas and nearby to reefs (Orpin et al., 1999; Passlow et al., 2005). Wave and tidal currents are active on the inner shelf throughout most of the year. Suspended terrigenous sediments become trapped in a turbid coastal boundary layer that is generated by waves and tides (Fig. 2.16) (Alongi and McKinnon, 2005). This forms in a narrow alongshore band of higher turbidity water in nearshore areas (<20 m water depth) and results in little exchange between inner and mid shelf waters (Wolanski, 1994; Woolfe and Larcombe, 1998; Brinkman et al., 2001). This turbid layer contains terrigenous mud resuspended from the seabed, which contains higher suspended sediment concentrations (SSC) than surrounding waters. Higher SSC concentrations occur during prolonged periods of strong southeast winds, and during storm and cyclone events. For example, near-bed SSC's recorded offshore Townsville, rarely exceed 40 mg l^{-1} most of the time. However, SSC can attain 200 mg l^{-1} at times of high swell generated by strong south easterly winds (Larcombe et al., 1995a; Fabricius and Wolanski, 2000). The structure and stability of the turbid coastal boundary layer is affected by the rugged coastline and has been shown to break down during storms, and at times of strong wind and high river discharge (Alongi and McKinnon, 2005).

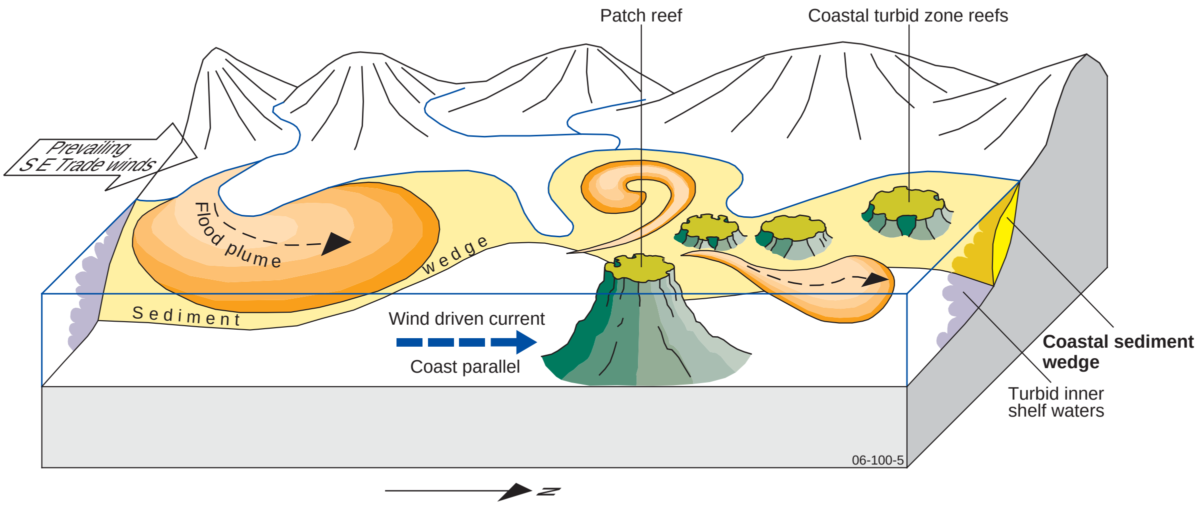

Figure 2.16. Schematic diagram of north-directed sediment movement on the inner shelf, showing the main oceanographic features of this zone (modified from Alongi and McKinnon, 2005).

The Queensland coast has an average mean annual rainfall of ~1,500 mm and between 14 to 28 Mt of terrigenous sediment is discharged from rivers into the GBR lagoon annually (Fig. 2.17) (Alongi and McKinnon, 2005). Flood plumes are generally confined to the inner-shelf but can extend up to 50 km from the coast, and generally move northward as a geostrophic density current (Wolanski, 1994; Devlin and Brodie, 2005). Most of the coarse material (sand and gravel) is deposited in the coastal zone close to the location of the river mouths. However, mud from the Fitzroy River flood plume associated with Cyclone Joy, drifted ~100 km offshore to impinge on reefs in the Capricorn-Bunker Group (Devlin et al., 2001). Mud particles suspended in flood plumes form turbid eddies in the lee of north-facing headlands, inner shelf reefs and islands (Fig. 2.16). Their dispersal is influenced by wind direction and strength (Devlin et al., 2001).

The regular passage of tropical cyclones is an important control on sediment transport (Larcombe and Carter, 2004). Tropical cyclones across the GBR shelf generate strong along-shelf currents and large waves that locally cause significant sediment transport (Pickard et al., 1977; Wolanski, 1994). Compared with fair-weather conditions, sediment transport rates can be up to 10 times larger during these storms, with sustained near-bed currents of between 0.6-1.4 m s^{-1} recorded during Cyclone Joy in December 1990 (Fig. 2.18) (Larcombe and Carter, 2004; Wolanski et al., 2005). Along-shelf currents of more than 1.3 m s^{-1} actively erode the seabed and mobilise bedload material (Larcombe and Carter, 2004). On the inner shelf, storm-currents have been shown to resuspend sediment to ~5.5 m and ~12 m water depth on the leeward and windward sides of reefs, respectively (Wolanski et al., 2005). Cyclones also generate wind waves capable of eroding and fragmenting the coral substrate (Wolanski, 1994). In addition, boulder deposits along the Cairns coast indicate that even higher energy seabed erosion events have taken place in the GBR region. These deposits are considered to have been caused by either a very large cyclone event or tsunami (Nott, 1997).

Cyclones maintain the regional shore-parallel sediment distribution pattern by partitioning sediment onto the outer part of the inner terrigenous sediment wedge and in inter-reef depocentres on the outer shelf (Fig. 2.19) (Larcombe and Carter, 2004). While the effects of the southeast trade winds are principally limited to the inner shelf, cyclone-generated currents are able to resuspend sediment on the middle shelf in greater water depths. The middle shelf has been termed the 'cyclone corridor' (Larcombe and Carter, 2004) where sediments are transported by 'cyclone pumping' (Johnson et al., 1986;

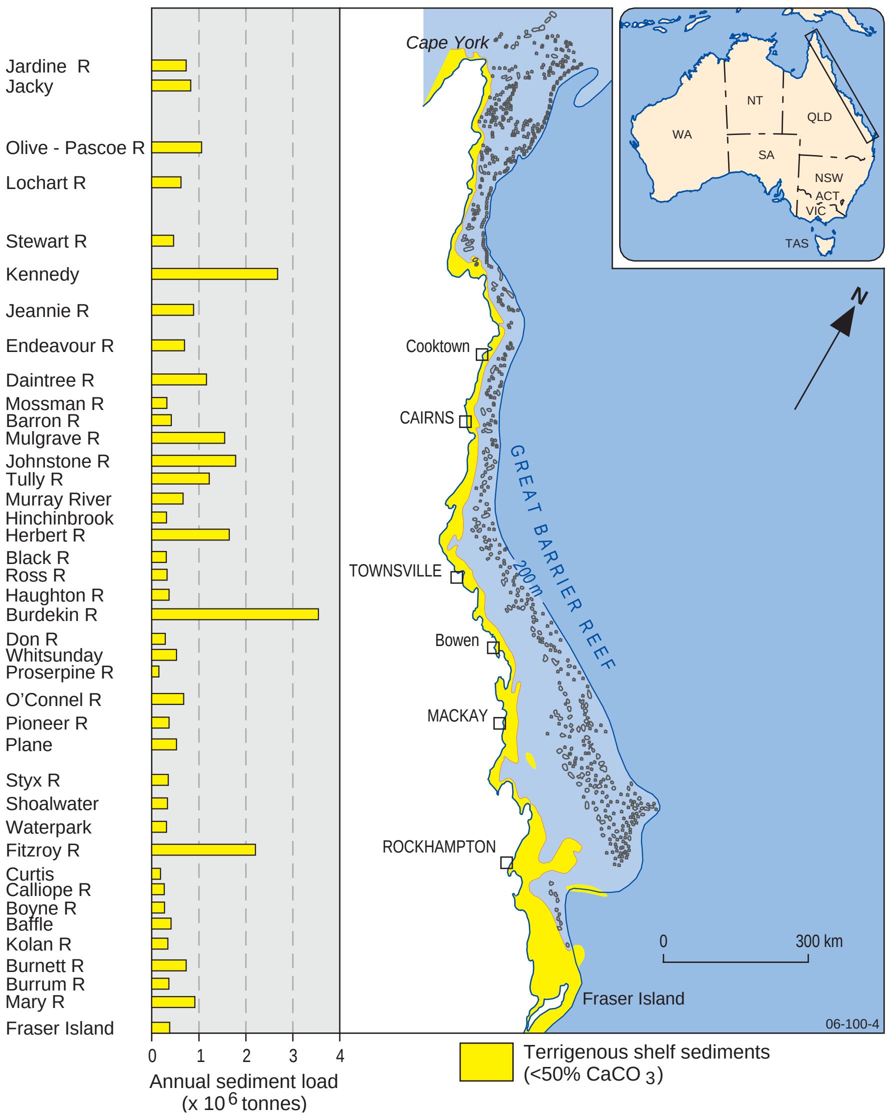

Figure 2.17. Average sediment load released onto the GBR lagoon annually (modified from Belperio, 1983). River catchments flowing into the GBR are highly seasonal systems, hence mean annual values of sediment load may be less representative over shorter time scales.

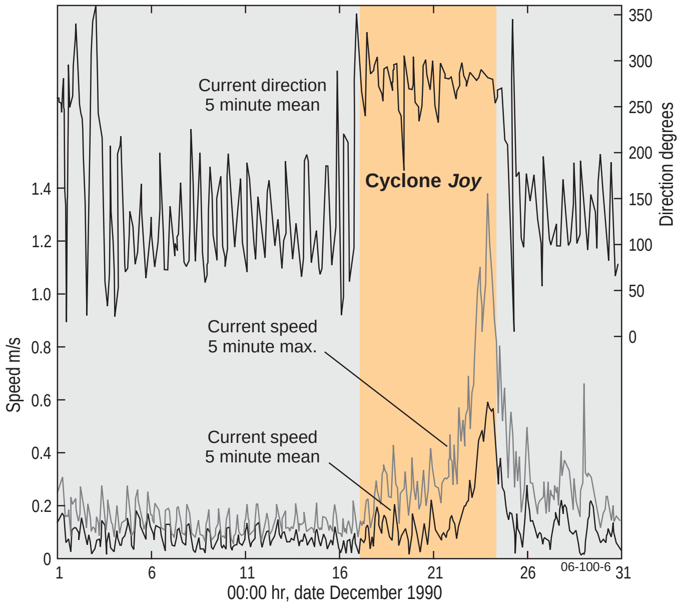

Figure 2.18. Current strength and direction measured in Trinity Bay, Cairns over a month long period, which captured the effects of Cyclone Joy during December 1990 (modified from Larcombe and Carter, 2004). Current measurements were taken 1 m above the seabed, in water depths of 12 m and shows the influence of the cyclone, which occurred over a 10 day period of along-shelf currents that peaked at 1.4 m s^{-1}.

Larcombe and Carter, 2004). Cyclone-generated currents scour and sweep the seabed, producing longitudinal bedforms (i.e. sand ribbons) and layers of poorly-sorted sediments on parts of middle shelf. Some cyclone events, such as Cyclone Winifred (Feb. 1986), can produce extensive storm beds blanketing widespread seabed areas, up to ~1,200 km^2 (Gagan et al., 1988).

The outer shelf region has a range of oceanographic processes, with physical hydrodynamic behaviour influenced by the irregular nature of the seabed between the shelf edge reefs. High-energy tidal and regional low-frequency currents, and upwelling, together force lagoon water shoreward. In inter-reef passages, strong across-shelf tidal currents are accelerated and 'pump' up-welled water shoreward. Complex three-dimensional flows, such as eddies, trap water within inter-reefal areas (Wolanski et al., 1988; Wolanski and King, 1990; Wolanski, 1994). The topographic variability and density of reefs produces a complex hydrodynamic setting. For example, current flow energy behind reefs can be dissipated by eddies and tidal friction associated with reef edifices during spring tides (i.e. sticky waters; Wolanski and Spagnol, 2000). In addition, the residence time of tides is prolonged in these areas (Wolanski and Spagnol, 2000). The variable bathymetry of the reef passages produces tidal jets of up-welled water during falling tides (Wolanski et al., 1988). These processes also control sediment dispersal, although there is little transport of carbonate sediments away from sediment wedges and the coral reef sediment source (Belperio and Searle, 1988). Often, up-welling and rapidly spreading surface waters over the shelf, remove sediments from the surface of reefs occurring at the shelf edge (Hopley, 1982; Brinkman et al., 2001). Strong inter-reef currents generated by localised upwelling, brings nutrient-rich waters into the lagoon. Such

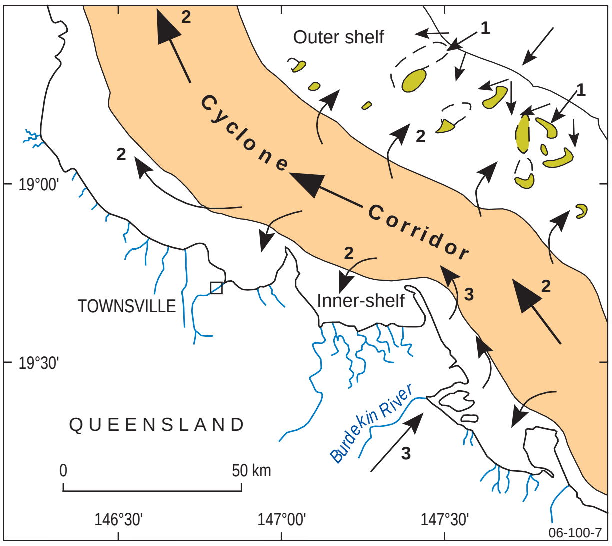

Figure 2.19. Conceptual model of the middle shelf cyclone corridor caused by cyclone pumping, which actively resuspends middle shelf sediments onto the shoreward side of the outer shelf zone and the ocean ward edge of the inner shelf (modified from Larcombe and Carter, 2004). Once cyclones have transported sediments across the shelf this is reworked by south easterly wind driven currents (Larcombe and Woolfe, 1999).

enrichments occur adjacent to *Halimeda* meadows in the northern GBR, which may be maintained by upwelled nutrient-rich water (Wolanski et al., 1988).

2.4. REGIONAL SEDIMENTOLOGY

The northeast continental margin of Australia forms the largest extant tropical mixed carbonate-siliciclastic depositional system in the world (Maxwell and Swinchatt, 1970; Davies and Peerdeman, 1998; Dunbar et al., 2000). Based on the shelf-parallel sediment zonation pattern, Belperio (1983a) broadly characterised the shelf into an inner, middle and outer shelf. Each zone has distinctive sediment compositions that can be more clearly defined by way of a systematic regional investigation. Modern seabed sediments on the GBR shelf are composed of terrigenous grains, derived from fluvial inputs and remobilised from shelf depocentres, and carbonate material, derived from in-situ production and inputs from shallow marine sources (Maxwell, 1968, Maxwell, 1973; Belperio, 1983a; Heap et al., 2002; Devlin and Brodie, 2005).

A Geoscience Australia report on the character and distribution of seabed sediments in the GBR has been compiled by Passlow et al. (2005). Maxwell (1968), Maxwell and Swinchatt (1970) and Maxwell (1973) first described the surface sedimentology of the GBR shelf, and recognised a decrease in terrigenous sediments towards the shelf edge. Belperio (1983a) was the first worker to illustrate the tripartite facies distribution pattern of sediments on the shelf. Scoffin and Tudhope (1985) describe in detail carbonate sediments on the central GBR outer shelf. Sedimentation in the GBR province was reviewed by Orme and Flood (1980).

2.4.1. Sediment Facies

Recent surface sediments form a veneer that overlies a pre-Holocene surface (locally referred to as reflector 'A': Johnson et al., 1982), which is a regional unconformity. This unconformity has been incised in some parts and also consists of high relief areas, which are principally located beneath modern reefs (Phipps, 1985). In the earliest regional synthesis, Maxwell (1968) classified surface sediments on the basis of carbonate content. In this classification, the high terrigenous facies of <20% carbonate in nearshore areas; the terrigenous facies with 20-40% carbonate in inner shelf regions; the transitional facies of 40-60% carbonate in a narrow middle shelf band; the impure carbonate facies with 60-80% carbonate in the middle shelf; and the high carbonate (>80%) facies, is restricted to the outer shelf adjacent to reefs (Fig. 2.20). Later, Belperio (1983a) developed a tripartite facies model for the GBR shelf. Sediment facies have a shelf-parallel distribution, which consists of a terrigenous-dominated inner shelf, mixed siliciclastic-carbonate middle shelf, and carbonate-dominated outer shelf (Belperio, 1983a; Belperio and Searle, 1988). The tripartite facies of Belperio (1983a) coincide with water depths on the shelf, of 0-20 m, 20-40 m and 40-~80 m respectively. These interpretations of the sediment facies distribution of the GBR province broadly reflect the provenance of terrigenous sediments from the western mainland, the supply of skeletal carbonate particles from biogenic production on the eastern outer shelf. The terrigenous and carbonate end-members are mixed on the middle shelf, where relict sediments also contribute to the overall supply of grains.

The tripartite sediment distribution is a product of the relatively shallow shelf gradient and limited cross-shelf transport of terrigenous and carbonate material away from their sources (Maxwell, 1968; Maxwell and Swinchatt, 1970; Belperio, 1983a). This facies distribution forms the modern mixed sedimentary system of the GBR province that has developed throughout the Quaternary (Larcombe and Carter, 2004). This work provides a context for the present study.

Shallow water, inner shelf sediment facies are characterised by terrigenous-dominated sand and mud grains (Figs. 2.20 and 2.22). The two end-member terrigenous components are blue-grey mud, which is derived from fluvial inputs, and quartz grains derived from continental islands (Orme et al., 1978). Terrigenous sediments generally comprise poorly-sorted muddy sand and fine sandy mud, which accumulate in high concentrations in a near-shore sediment wedge (Lambeck and Woolfe, 2000). The wedge attains thicknesses of 5 m to 10 m near river mouths and in north-facing embayments, reducing in thickness to only a few metres away from these depocentres and terminating in water depths of 20-22 m (Belperio and Searle, 1988; Carter et al., 1993; Woolfe and Larcombe, 1998; Orpin et al., 2004). Mud concentrations generally reach 40%, but can exceed 80% in north-facing embayments, with changes reflecting north-directed transport and point-source fluvial inputs (Cook and Mayo, 1978; Woolfe et al., 2000; Orpin et al., 2004; Ryan et al., 2007). Terrigenous sediment deposits are also found on the leeward side of continental islands.

The middle shelf facies is comprised of mixed siliciclastic-carbonate sediments that include terrigenous clays and shallow marine carbonates (Heap et al., 2001). It generally comprises a thin (<2 m thick) sediment veneer of poorly sorted, calcareous muddy sand (Johnson et al., 1986; Harris et al., 1990; Carter et al., 1993). In Nara Inlet in the Whitsunday Islands on the central GBR, Holocene sediments are 15-30 m thick (Heap et al., 2001). Generally, thin sediments overly the pre-Holocene (e.g. Pleistocene) surface,

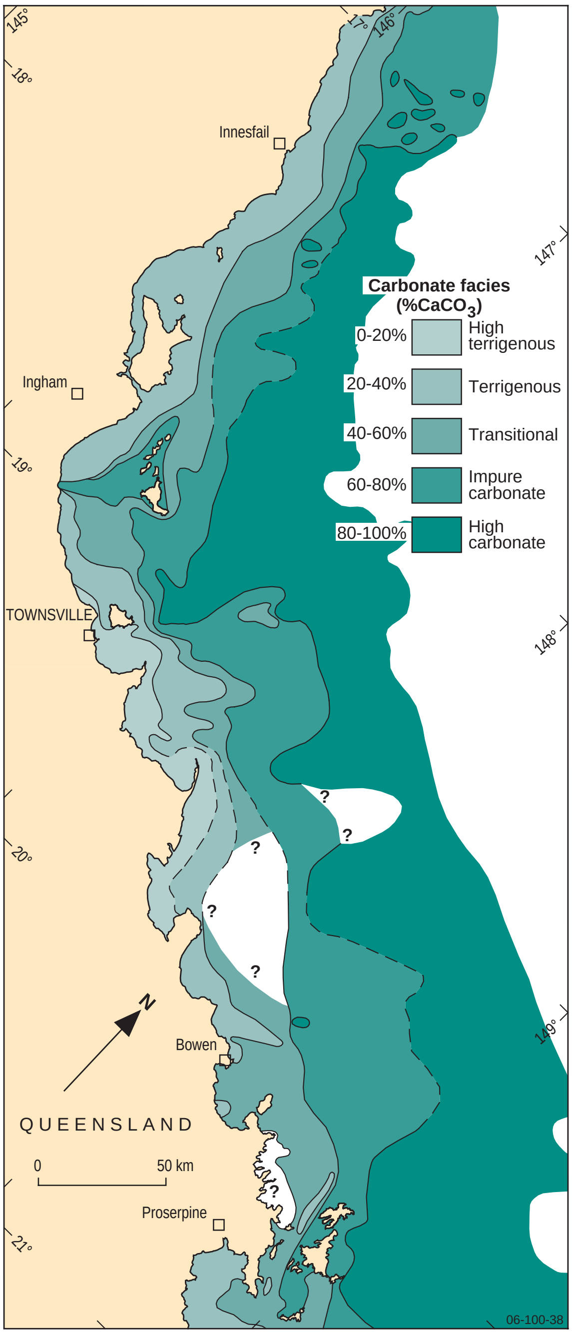

Figure 2.20. Carbonate content of sediments in the Townsville-Whitsunday Management section of the GBR marine park (modified from Maxwell, 1973). Carbonate content exhibits a shore-parallel zonation with respect to the coast; with low carbonate facies occurring inshore, compared with high carbonate facies furthest offshore. ? indicate areas of no data.

with sparse outcrops of older hard substrate, such as Pleistocene clays protruding through the thin sediment veneer (Johnson et al., 1986). Sand is locally deposited in sandwaves and longitudinal dunes (Johnson et al., 1986). Thick sequences of unconsolidated mixed siliciclastic-carbonate sediment also occur around islands, in shelf depocentres far from fluvial point sources (Johnson and Searle, 1984, Heap et al., 2002).

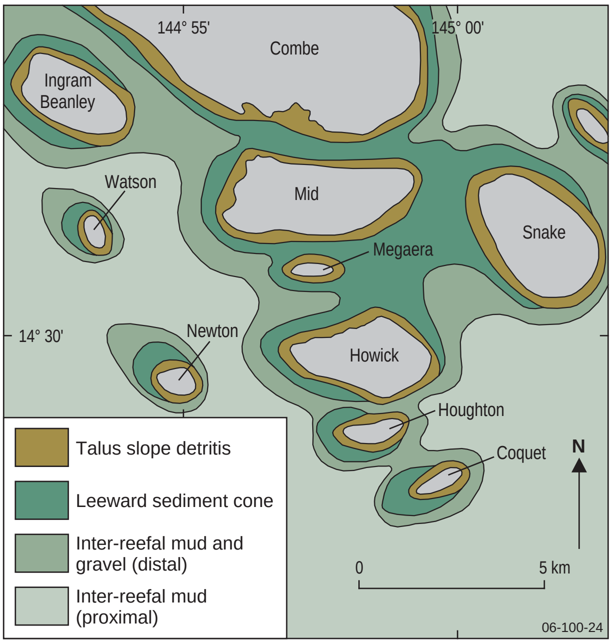

Figure 2.21. An example of reef facies from the Howick Group region, showing the concentric distribution pattern of textural sediment types surrounding reefs (modified from Flood et al., 1978). Sediments up to 2 km away from reefs are influenced by the reefs. Such sediments include; 1) reef-proximal talus slope sediments of coarse coral detritus and benthic foraminifera; 2) leeward sediment cone of skeletal detritus; 3) a mixture of reef material, in situ organisms and terrigenous mud; and 4) reef-distal (shelf) sediments of skeletal gravel and sand, and terrigenous mud.

The outer shelf facies is characterised by high concentrations of calcareous sediment, which accumulates on inter-reefal seabed areas (Maxwell, 1968) (Fig. 2.20). Sediment thicknesses are variable, and range from <1 m thick in inter-reefal areas, to several metres thick in *Halimeda* banks (Scoffin and Tudhope, 1985). Surface sediment distributions are highly complex on the outer shelf and surrounding reefs (Fig. 2.21). Concentric facies types have been identified around reefs, separated by wide expanses of shelf sediments. Seven facies types have been recognised on the central GBR outer shelf by Scoffin and Tudhope (1985). In general, outer shelf sediments comprise isolated deposits of highly bioturbated fine lagoonal sands; carbonate gravel and coarse sand on reef flats, rimmed by shingle banks; surrounded by coarse leeward talus slopes of coarse carbonate sand and gravel, which are separated by a blanket of inter-reefal foraminiferal sand and gravel (Maxwell, 1968; Scoffin and Tudhope, 1985; Flood and Orme, 1988). The shelf edge is draped by pelagic bioclastic and nanno-fossil oozes (Davies et al., 1991).

2.4.2. Sediment Texture and Composition

Sediments are described in terms of their texture and composition and provide insights into the nature of the GBR seabed. The distribution and physical attributes of siliciclastic terrigenous and biogenic carbonate grain types are described. Terrigenous components show two dominant end-member sediment types, and there are several skeletal carbonate grain types that occur in varying concentrations.

Terrigenous mud is a significant component of riverine and estuarine sediment deposited on the inner shelf. These particles consist of inorganic material including clays such as kaolinite, smectite and illite, silicate sand, organic detrital particles and living plankton, with calcareous sand comprising a very small part (Fabricius and Wolanski, 2000; Ward et al., 1995). Mud particles are comprised of flocculated clay flakes that are blue-grey in colour (Orme and Flood, 1980). Such particles are originally derived from the chemical weathering of a range of rock types, which vary depending on the catchment source. Mud content ranges from 20-60 % in inner shelf regions, and decreases to 1-20% on the outer shelf (Fig. 2.22) (Passlow et al., 2005). Higher concentrations of 60-80% occur north of Cairns in Princess Charlotte Bay.

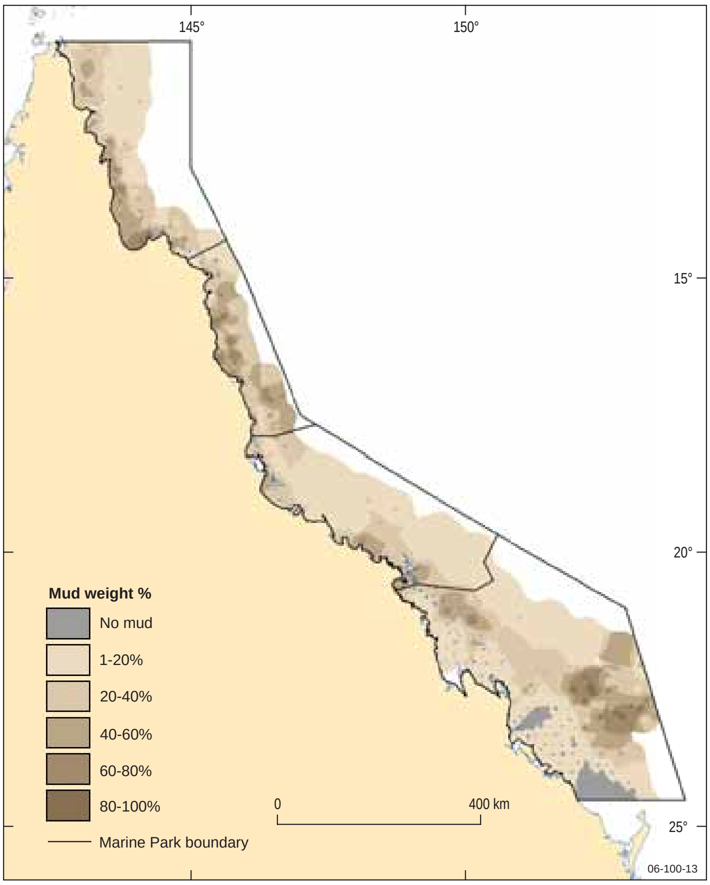

Figure 2.22. Percent mud concentration on the GBR shelf, showing broad distribution patterns of high mud adjacent to riverine outflows on the inner shelf, and low mud contents nearby to reefs on the outer shelf where carbonate content dominate seabed sediments (from Passlow et al., 2005).

Quartz grains are locally abundant and occur on the inner shelf, near continental islands, the scoured windward margins of reefs and bioturbated inter-reefal areas (Ward et al., 1995; Scoffin and Tudhope, 1985). Quartz is typically a component of the sand and gravel fraction (Fig. 2.23, 2.25) (Flood and Orme, 1988). Pockets of quartz rich sediment reach maximum concentrations in the Burdekin River delta (78%), off Cape Sandwich (78%), north of Cape Tribulation (80%), Cape Flattery (86%), and Newcastle Bay (100%) (Lambeck and Woolfe, 2000). Quartz dominates sediments in southern Halifax and Cleveland Bays, where it comprises 50% of sediment components (Ward et al., 1995). Nearby continental islands such as Lizard Island, terrigenous deposits are quartz rich, but also consist of other components such as feldspar, mica, tourmaline and minor fragments of granite, beachrock and relict carbonate grains (Orme et al., 1978). In general, the concentration of mineral grains such as quartz, feldspar, hornblende and pyroxene increase with proximity to major rivers and decrease north from fluvial point sources (Lambeck and Woolfe, 2000). Close to outer shelf reefs, quartz grains are mature, commonly rounded and well sorted relict grains (Scoffin and Tudhope, 1985). Such concentrations of siliciclastic grains often reflect weathering and transport from a continental source, but can also be derived from eroded older Pleistocene substrate (Scoffin and Tudhope, 1985; Heap et al., 2002).

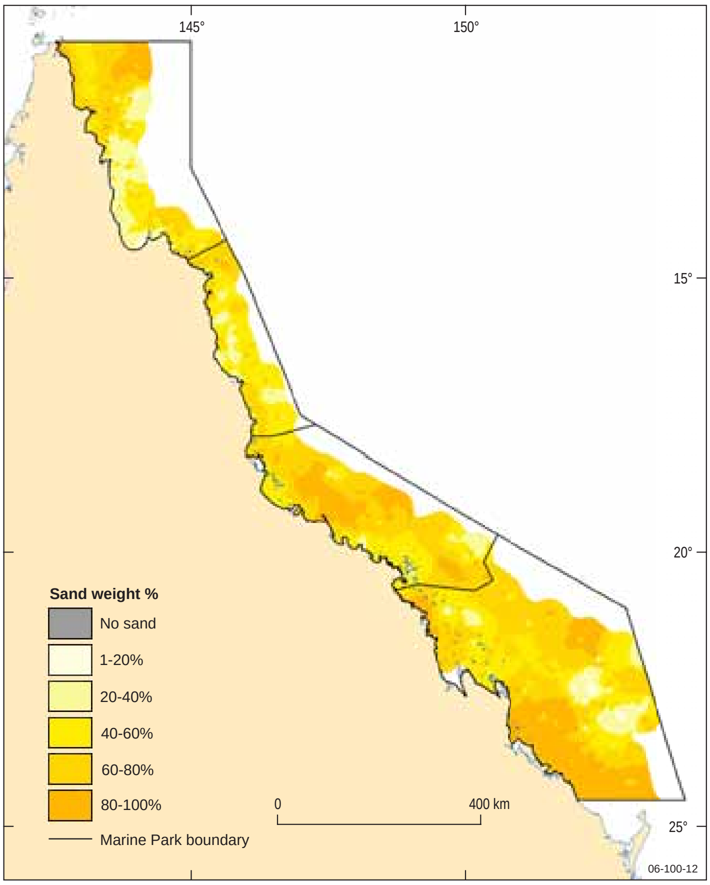

Figure 2.23. Percent sand content in surface sediments on the GBR shelf (from Passlow et al., 2005).

The carbonate content of sediment on the GBR shelf is dominated by biogenic grains and is generally derived from contemporary skeletons of biota accumulated in situ (Flood et al., 1978). Carbonate concentrations increase from west to east across the shelf, and attain ~40% within 20 km of the coast and exceed 90% in inter-reefal seabed areas on the outer shelf (Fig. 2.20, 2.24) (Maxwell, 1968). Carbonate concentrations are typically between 20-40%, 60-80% on the middle shelf, and 80-100% on the outer shelf (Passlow et al., 2005). Most carbonate grains are sand- and gravel-sized, and increases in carbonate concentrations across the shelf are mirrored by increases in the gravel content (Figs. 2.23-2.25) (Scoffin and Tudhope, 1985). Carbonate grains are principally composed of the skeletal remains of foraminifers, molluscs, *Halimeda*, coralline algae, coral rubble, bryozoans, echinoderms and serpulids (Belperio, 1983a). Benthic foraminifera, *Halimeda* and molluscs are the major producers of calcium carbonate to the shelf sediments of the

GBR (Scoffin and Tudhope, 1985). According to Maxwell (1968), sources of carbonate sediment to the GBR seabed are 17-40% coralline algae, 20-40% coral, 10-30% *Halimeda*, 8-20% foraminifera, 4-15% molluscs and <5% of echinoid, bryozoan and crustacean fragments. The distribution of skeletal grains vary latitudinally across the shelf, controlled by reef density, bathymetry and shelf width, tidal currents and the influence of relict deposits (Orme and Flood, 1980). Generally, higher carbonate concentrations occur on the outer parts of the shelf. Changes in skeletal grains also occur in a longitudinal, along-shelf direction (Marshall and Davies, 1978) (Fig. 2.26). As well as modern skeletal material,

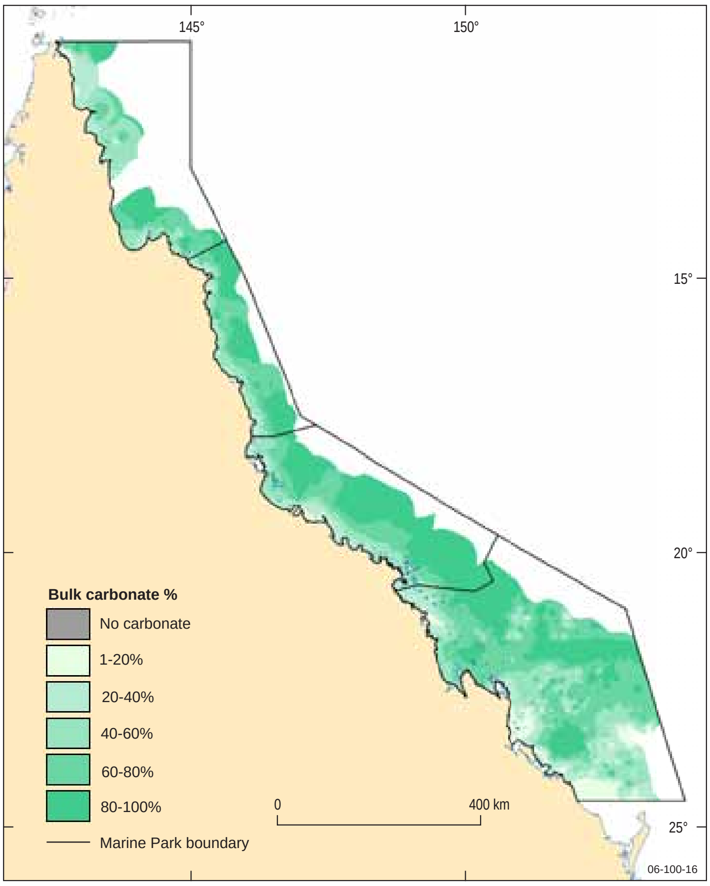

Figure 2.24. Percent carbonate in surficial sediments, with concentrations of less than 30 % on the central GBR inner shelf and increase nearby reefs in outer shelf regions to 80-100 % (from Passlow et al., 2005).

relict grains from ancient faunas eroded from underlying sediments are also present (Maxwell, 1968). Relict formainifera represent a high percentage of all foraminiferal tests, in particular *Marginopora* and *Alveolinella* (Maxwell, 1968). Sediments in inter-reefal areas of the central GBR are composed mostly of benthic foraminifera and *Halimeda* grains (Scoffin and Tudhope, 1985; Harris et al., 1990).

Foraminifera are a common component of surface sediments and are present in all sedimentary environments across the GBR (e.g., Maiklem, 1966; Flood and Orme, 1988; Harris et al., 1990; Heap et al., 2001; Horton et al., 2003, King et al., 2004). Benthic and pelagic species show strong shelf-parallel distributions related to water depth, except on the broad southern shelf where tidal currents modify the occurrence of pelagic species (Fig. 2.27) (Maxwell, 1973). Five facies types have been recognised (Orme and Flood, 1980), and include the non-foraminiferal facies (<5%), the low foraminiferal facies (5-10%), the moderate foraminiferal facies (10-20%), the high foraminiferal facies (20-30%), and the very high foraminiferal facies (>30%). Concentrations of benthic foraminifera are high in inter-reefal sediments on the outer shelf, where they can attain > 60% (Maxwell and Swinchatt, 1970; Flood and Orme, 1988). A few of the more common benthic foraminifera species on the middle and outer shelf include; *Operculina bartschi*, *Cellanthus craticulatum* and *Amphistegina quoyi* (Lloyd, 1973). *Amphisorus sp*. is abundant on and near reefs, and encrusting foraminifera such as *Homotrema rubrum* and *Gypsina* are associated with coarse

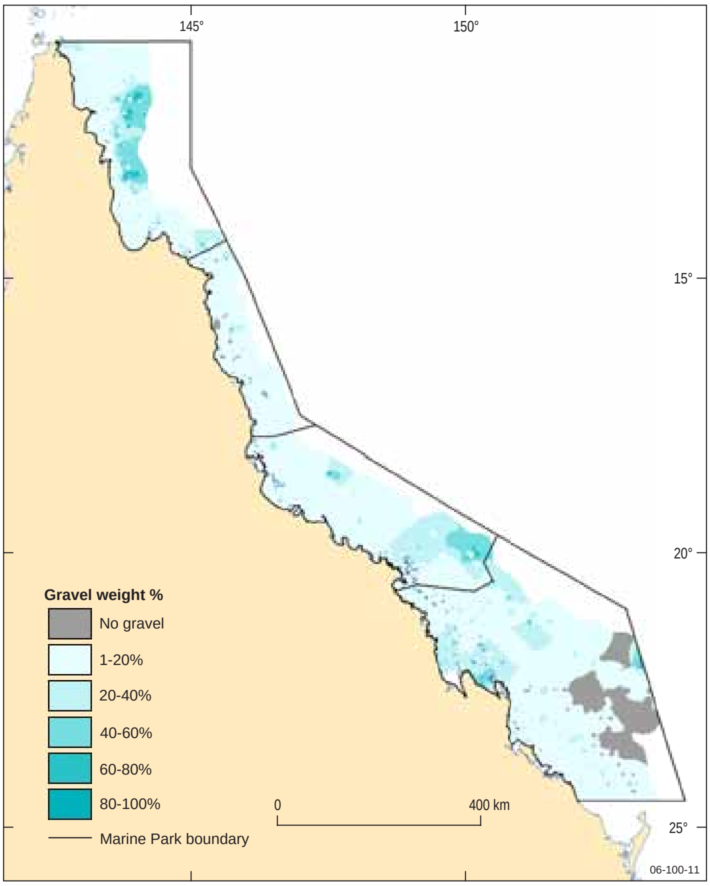

Figure 2.25. Percent gravel content actoss the GBR shelf (from Passlow et al., 2005).

sediment derived from local rock outcrops (Scoffin and Tudhope, 1985). *Cycloclypeus carpenteri* is abundant in deep water at the shelf edge. On the open shelf between 17°S and 20°30S, where other calcareous components have lower concentrations, foraminifera are a common constituent (Maxwell, 1973).

Mollusc shells and fragments are a ubiquitous sediment component and occur in all sedimentary environments (e.g., Maxwell and Swinchatt, 1970; Maxwell, 1973; Heap et al., 2001). Mollusc concentrations exceed 40% on the middle shelf and inter-reef plains and passages, where contributions from other sources (e.g. corals) are lower (Fig. 2.27) (Maiklem, 1966). Molluscs are particularly abundant in sheltered inter-reef areas (e.g. Swains Complex), near reefs and in shallow reef lagoons, but can be as low as <10% on the fore-reef slopes on the outer shelf (Orme et al., 1978). Gastropods, bivalves and

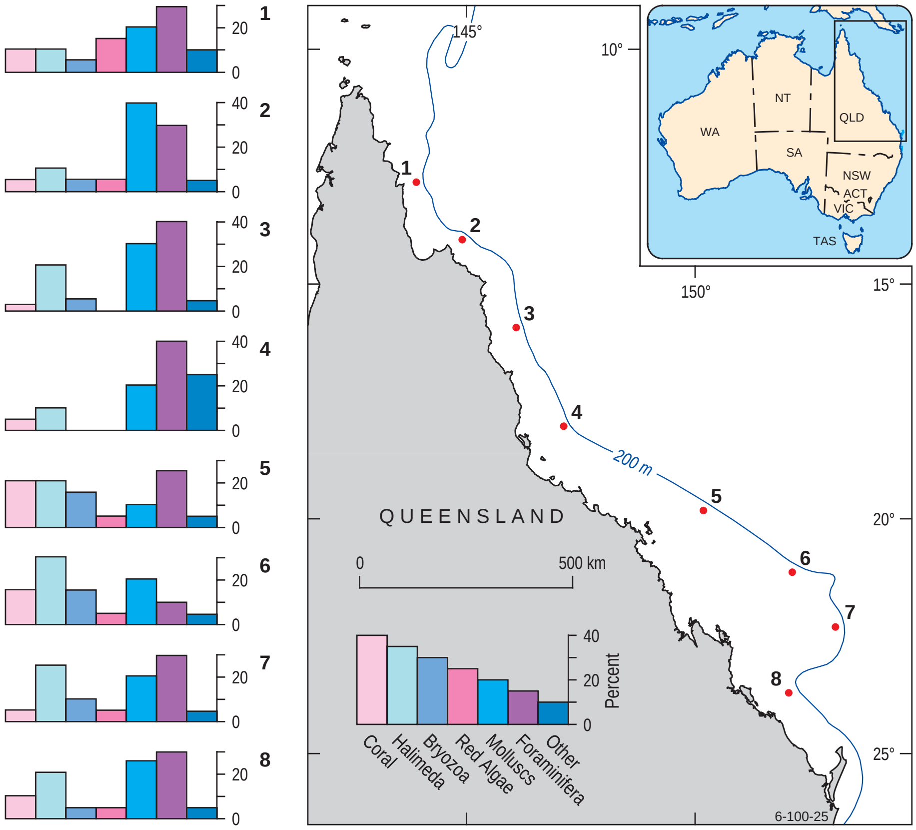

Figure 2.26. Histograms showing the variation in skeletal carbonate components on the outer continental shelf (modified from Marshall and Davies, 1978). Graphs show the overall predominance of molluscs and foraminiferans as the primary contributors to skeletal carbonate, and the variable contribution of coral to skeletal components along the shelf.

pelecypods are the dominant constituents, in order of decreasing abundance (Scoffin and Tudhope, 1985). Thick-shelled bivalves are more common than the thin-shelled equivalent. The abundance of mollusc fragments is inversely proportional to the concentration of coral fragments.

Halimeda particles form a significant component of outer shelf sediments (Fig. 2.26) (e.g. high *Halimeda* facies; Scoffin and Tudhope, 1985) (Orme, 1985; Orme and Salama, 1988; Flood and Orme, 1988). *Halimeda* meadows are extensive and are a major source of carbonate grains. On the outer shelf, extensive *Halimeda* banks up to 18 m thick and 3-4 km long occur landward of the reefs (Orme et al., 1978; Flood and Orme, 1988). *Halimeda*-dominated sediments are composed of gravel- and sand-sized particles of whole and fragmented *Halimeda* plates (Flood and Orme, 1988). Concentrations locally attain 70-90% in inter-reefal sediments on the outer shelf, and are typically <1% on the inner shelf (Orme et al., 1978). Some outer shelf sediment samples obtained from the central GBR contain whole and articulated segments, and living branches of *Halimeda hederacea* (Scoffin and Tudhope, 1985). *Halimeda* gravel deposits form stratified banks <18 m thick and provide a suitable substrate for encrusting foraminifera and calcareous red algae. Dominant species in shallow water settings are *Halimeda opuntia* and *Halimeda copiosa*, while *Halimeda hederacea* is predominant in deeper waters (Scoffin and Tudhope, 1985).

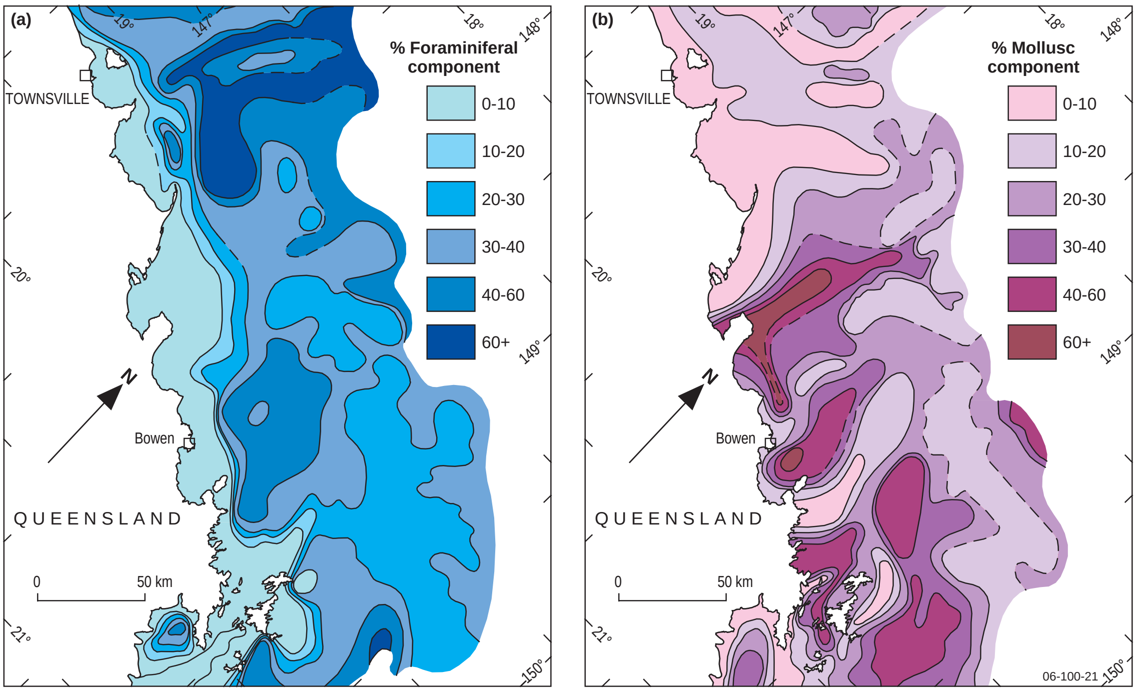

Figure 2.27. Contoured foraminifera (a) and mollusc (b) concentrations on the central parts of the continental shelf (modified from Maxwell, 1973); (a) shows an increase in foraminifera contents furthest offshore; and, (b) shows the highest mollusc concentrations occur on shallower, inner and middle parts of the shelf.

Coralline algale fragments comprise >5% of inter-reefal sediment on the shelf (Orme and Flood, 1980). The abundance of coralline algae is closely related to reef density with encrusting red algae common on the reef framework (Orme and Flood, 1980). Extensive pavements of crustose coralline algae occur on the reef crests, and decrease with distance away from the reef top (Klumpp and McKinnon, 1989). Articulated forms of coralline algae occupy areas away from the reef crest.

Coral rubble generally makes up <10% of sediment grains near reefs on the outer shelf because it is diluted by non-reefal components (Fig. 2.26) (Orme and Flood, 1980; Scoffin and Tudhope, 1985). Coral is only abundant adjacent to reefs and submerged rocky substrates (Scoffin and Tudhope, 1985; Ryan et al., 2001). Coral rubble accumulates as reef talus slopes, which are often poorly sorted (e.g. Lizard Island; Hughes, 1999). Dead coral branches make up a large proportion of coral rubble, with a minor component of living material. The shallow-water coral, *Acropora sp*. contributes fragments to the prograding talus wedge of Davies Reef and to lagoonal sediments (Scoffin and Tudhope, 1985). *Seriatopora hystrix* is abundant in the sediment of shallow rocky edifices (Scoffin and Tudhope, 1985). On the outer shelf, fragments of unattached solitary corals such as *Cycloseris sp*. and *Diaseris sp*. are common sediment components (Scoffin and Tudhope, 1985).

Other skeletal components such as bryozoans, serpulids and echinoderms contribute minor amounts to overall shelf sediment (Fig. 2.26). Bryozoans are common in coarse sediment near rocky substrates, where branched forms are found. Fine encrusting types are common on gravel fragments and relic grains (Scoffin and Tudhope, 1985). Bryozoans are more developed in the southern parts of the province (>15%), where the wide shelf environment is suitable for growth (Orme and Flood, 1980). Echinoderms make up a small component of all sediments, and comprise echinoid plates and spines and crinoid ossicles (Scoffin and Tudhope, 1985). Echinoderm skeletons occur in mud and muddy sand sediment on the inner shelf, and comprise >5% of sediment in these areas. The contribution of serpulid skeletons is typically <1% of all sediment, but they are found in higher numbers near rocky outcrops at the shelf edge (Scoffin and Tudhope, 1985).

Ooids are uncommon, but have been identified in relatively high concentrations (>40%) between Swain and Capricorn Reefs in Capricorn Channel (Marshall and Davies, 1974) and near Lizard Island (Davies and Martin, 1976). In Capricorn Channel, ooids occur in water depths of 100-120 m and have been sampled over an area of 340 km^2. These ooids are inferred to have initially formed in the early Holocene and are composed of high-magnesium calcite (Marshall and Davies, 1974; Yokoyama et al., 2006).

A significant proportion of calcareous and siliciclastic material on the GBR shelf is relict (Maxwell, 1968; Heap et al., 2002). Relict sediments are derived from an environment that is unrelated to that in which they presently occur, and may be stained and/or altered. Relict quartz sand and skeletal carbonate make up significant proportions of the relict sediment. Relict quartz sand comes from reworking of former fluvial and coastal facies that were presumably emplaced during lowstand, and locally from granite islands (Belperio, 1983a; Belperio and Searle, 1988; Heap et al., 2002). Relict carbonate grains typically comprise recrystallised, stained (i.e. altered) or encrusted benthic foraminifera, which are light and dark brown, to black in colour (Scoffin and Tudhope, 1985). On the inner shelf, abundant, black-stained foraminifera tests of *Marginopora* sp. and *Alveolinella* sp. locally comprise up to 20% of sediment, producing distinctive 'speckled sands' (Maiklem, 1966; Maxwell, 1968). Such fauna has probably been eroded and reworked from old reef surfaces (Maxwell, 1968).

3. Methods

This report uses the results of six recent marine surveys funded by Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australian Institute of Marine Science (AIMS), Queensland Department of Primary Industries (QDPI) and the Queensland Museum (QM), these include; AIMS3465 (GBR #1), AIMS3469 (GBR #2), AIMS3481 (GBR #3), AIMS3737 (GBR #4), AIMS3746 (GBR #5), and AIMS3976 (GBR #6). A total of seven surveys were conducted from September 2003 (for #1) to November 2005 (for #6), using the research vessels RV *Lady Basten* (surveys 1-6) and *James Kirby* in Torres Strait (survey results contained in a separate report to be published at a later date). In addition, the sediment sample data obtained from many previous surveys of the GBR will also be included in this report. This data is held in Geoscience Australia's MARS database (www.ga.gov.au/oracle/mars).

3.1. SAMPLE ACQUISITION

Data for a total of 2,955 stations were acquired during both the recent AIMS surveys (Fig. 3.1) and many other previous surveys (Fig. 3.2). The locations of the stations were designed to capture the full spectrum of non-reefal sedimentary environments and seabed habitats throughout the GBR. Samples were collected from the inner, middle and outer shelves and continental slope, in water depths ranging from <5 m to ~2,000 m (Table 3.1). The continental slope is under represented by samples .

Table 3.1. Number of samples and stations from AIMS and other surveys that were recovered from each shelf region.

Seabed region	Samples			Stations		
	AIMS	Other	All	AIMS	Other	All
Inner shelf	264	415	679	263	405	668
Middle shelf	350	970	1320	348	911	1259
Outer shelf	502	410	912	501	404	905
Continental slope	34	94	128	34	89	123
Total	1150	1889	3039	1146	1809	2955

Samples were collected from the seabed using a pipe dredge deployed from the ship's A-frame (Fig.3.3). Each dredge was dragged behind the ship along the seabed for approximately 500 m on approach to the sample waypoint. Time and coordinate location was recorded at the start and termination of each winching operation. Once on board, each sample was then sub-sampled for bulk sediment, and biota where possible. A representative sample (sub-sample A; e.g., 266/4GR4A) was obtained for bulk sediment (500 ml), which was weighed and given a brief qualitative textural description. Another 500 ml sub-sample was washed and sieved through 1 mm sized mesh and then preserved in a solution of rose-bengal / formalin (sub-sample B; e.g., 266/4GR4B). It is intended that the sieved biological sample will be used to identify and collect present biota, which will be undertaken as part of the GBR Seabed Biodiversity Project. Samples were stored in an air conditioned (~24°C) hold on board the RV *Lady Basten*. Details of the surface sediment samples were entered into the Geoscience Australia's MARS database.

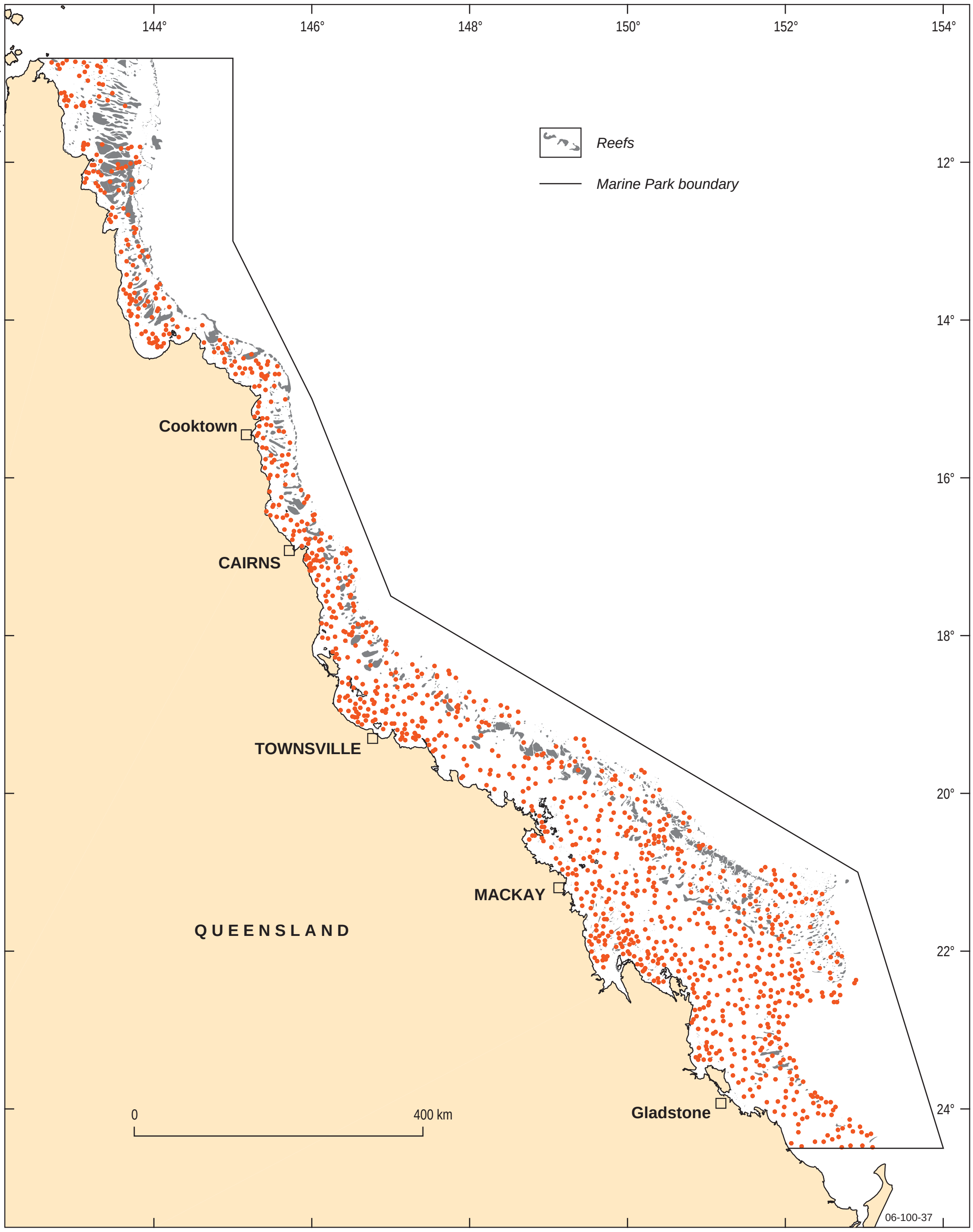

Figure 3.1. Diagram showing the distribution of AIMS samples acquired across the entire GBR shelf.

Sediment samples from previous work have been obtained from dredge, grab (i.e. ship deck, smith mcintyre, van veen and unspecified), box core, core top (i.e. push, piston, vibro and gravity corer) and core catcher sampling. Together, each bulk sample from the AIMS and previous surveys were sub-sampled for grain size and/or carbonate sediment analysis. The distribution of these samples within each of the four Marine Park management sections, is not uniform (Figs. 3.4-3.7).

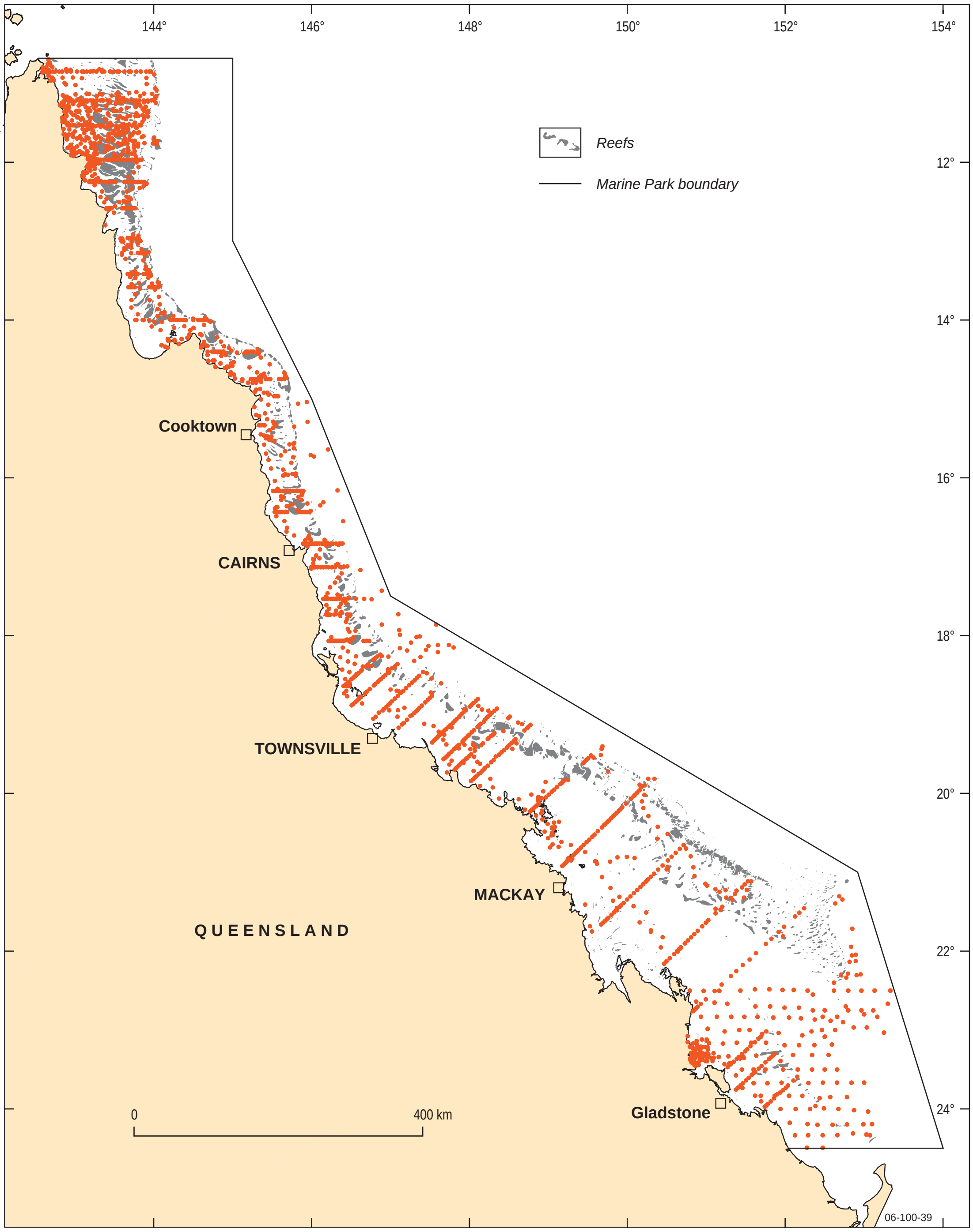

Figure 3.2. Diagram showing the distribution of all 'other' samples acquired across the entire GBR shelf.

3.2. SAMPLE PROCESSING AND ANALYSIS

3.2.1. Sediment texture

Initially, the bulk sample was split into two sub-samples for grain size analysis. Bulk grain size distributions were determined for the first sub-sample using a Malvern™ Mastersizer-2000 laser particle size analyser (e.g., Heap et al., 1999). The bulk sample was sieved through a 2 mm mesh to remove the gravel fraction, which was retained for visual

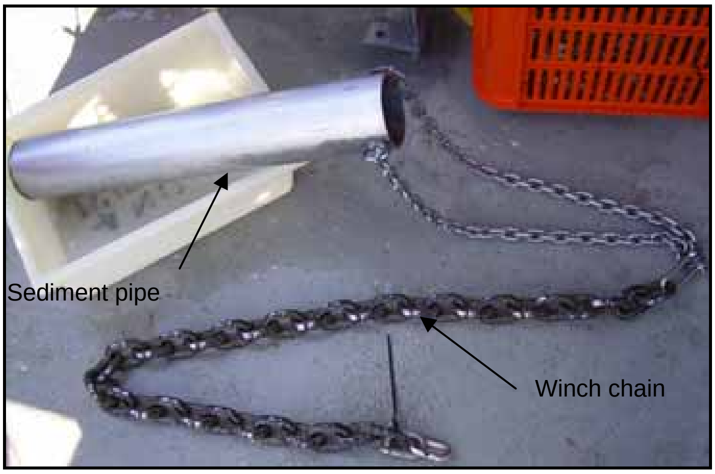

Figure 3.3. Photograph of the pipe dredge used for collecting surficial sediment and biota (courtesy of R. Pitcher, CSIRO). The pipe dredge recovers sediment from a linear path as it is towed across the seabed. This dredge has a volume of ~ 4 litres and weighs 7 kg with no contents and ~ 11-15 kg when full.

inspection. Organic matter in the fine fraction was then removed by immersing the sample in 10-20 ml of dilute hydrogen peroxide (H_2O_2). After rinsing thoroughly with distilled water, the sample was placed in an ultrasonic bath for up to 2 mins to break up any remaining aggregates. The grain size distribution of the fine fraction was then determined using the laser particle size analyser.

Approximately 10-20 g of the second sub-sample was sieved through a 2 mm and 63 μm sieve with distilled water. Each size fraction was retained. The mud fraction was spun in a centrifuge at 3,500 rpm for 10 mins to separate out the sample. All of the fractions were dried in an oven at 40° C for at least 24 hours and then allowed to cool to room temperature. The dried material for each fraction was then weighed with an analytical balance to obtain the amount of gravel, sand and mud in the sample.

3.2.2. Sediment composition

Carbonate concentrations were determined on all of the bulk samples, as well as the sand and mud fractions using the "carbonate bomb" method of Muller and Gastner (1971). Initially the 3-5 g of bulk sample was dried in an oven at 40° C for 24 hours. This sample was then ground to a fine powder and exactly 0.8 g was reacted with 10 ml of orthophosphoric acid (H_3PO_4). The flask was agitated until the entire sample had reacted with the acid (usually about 60 s). The pressure of the gas liberated was then compared to a standard curve that converted the pressure into carbonate concentrations (the curve is constructed by reacting known amounts of pure calcium carbonate between 0.1 – 0.8 g and recording the corresponding pressure). The carbonate content of the gravel fraction was estimated from a visual inspection for all samples.

Select samples were visually inspected for composition on board the vessel and in the laboratory using a standard binocular microscope. The bulk, gravel, sand and mud fractions were inspected separately, with only the coarse silt-sized grains visible in the mud fraction. An estimate of the abundance of each constituent in each fraction was made based on a visual assessment of the grains.

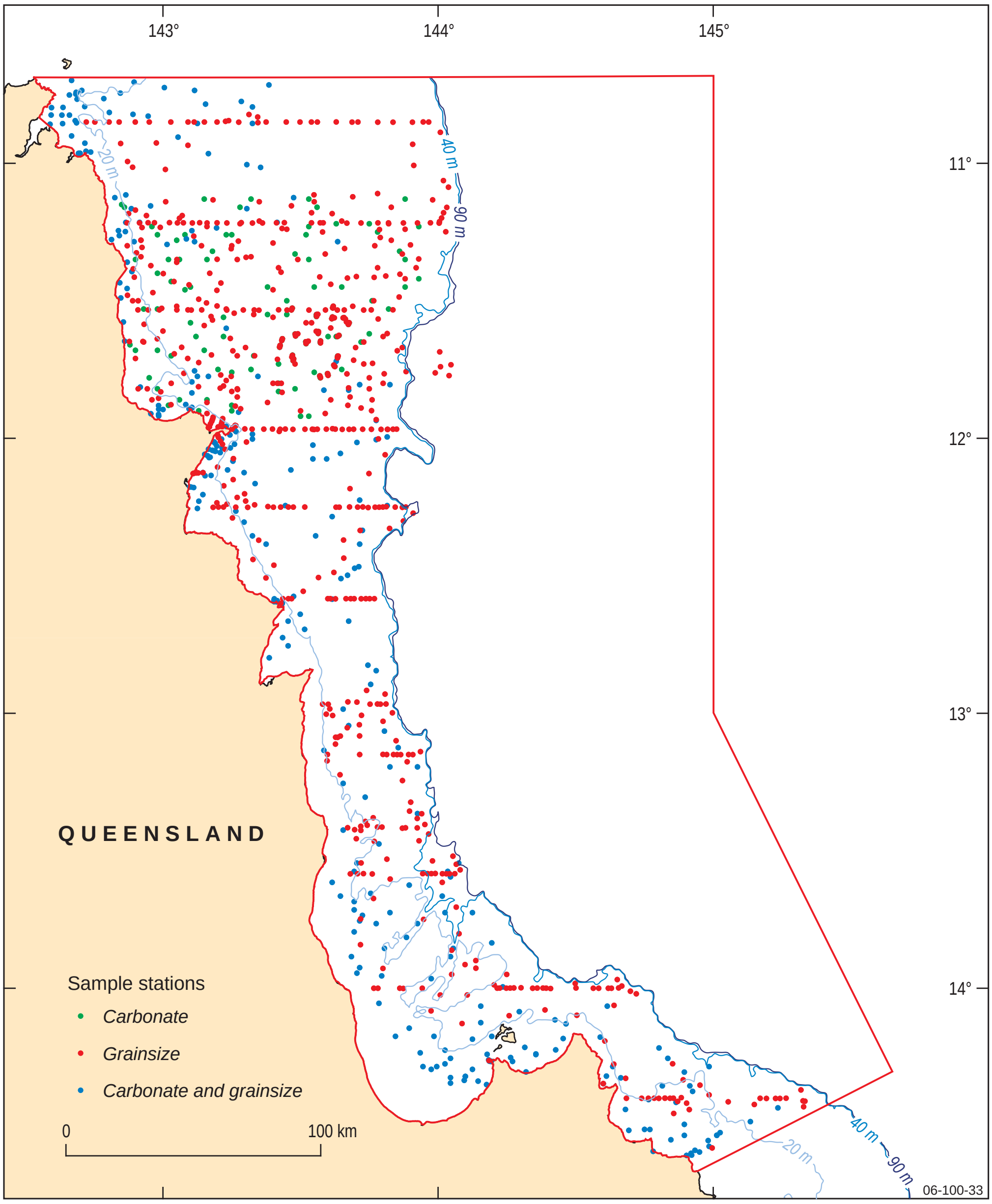

Figure 3.4. Sample stations across the shelf, within the Far Northern Management Area of the GBR Marine Park. Stations where: a) carbonate; b) grainsize; and c) both carbonate and grainsize samples were collected, with divisions between the inner, middle and outer shelves shown with blue lines.

3.3. DATA PROCESSING AND ANALYSIS

3.3.1. Sample station locations

As dredge locations were predetermined by station way points prior to the survey, the exact location of sample sites needed to be calculated. Correct latitude and longitude coordinates for each sample was processed post-survey, to account for location inaccuracies that may have developed during survey dredging operations.

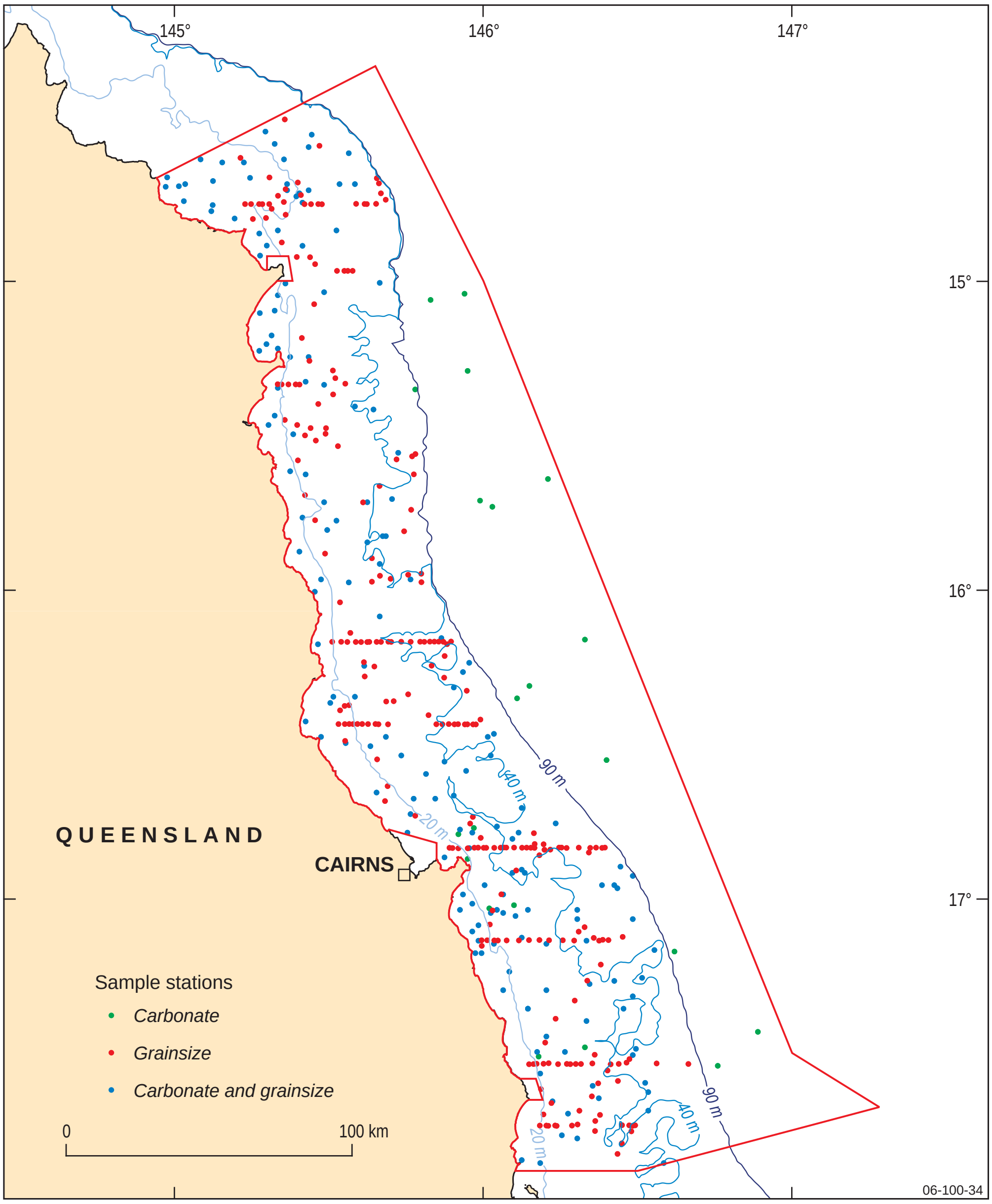

Figure 3.5. Sample stations across the shelf, within the Cairns/Cooktown Management Area of the GBR Marine Park. Stations where: a) carbonate; b) grainsize; and c) both carbonate and grainsize samples were collected, with divisions between the inner, middle and outer shelves shown with blue lines.

3.3.2. Sediment Attribute Data

3.3.2.1. Folk classification

Sieve sediment data was texturally classified into the Folk (1964) classification scheme (Fig. 3.8) using the GRADISTAT grain size statistics program (version 4.0; Blott and Pye, 2001). Folk statistics were generated by entering up to 230 of the AIMS samples into the 'multiple sample data input' calculator. This was undertaken four times to obtain folk grain size statistics for samples from the inner, middle and outer shelves, and continental slope. The output provided a folk classification of each sample which was then mapped in the GIS to obtain the spatial distribution of Folk texture. See general processing procedure below for map generation.

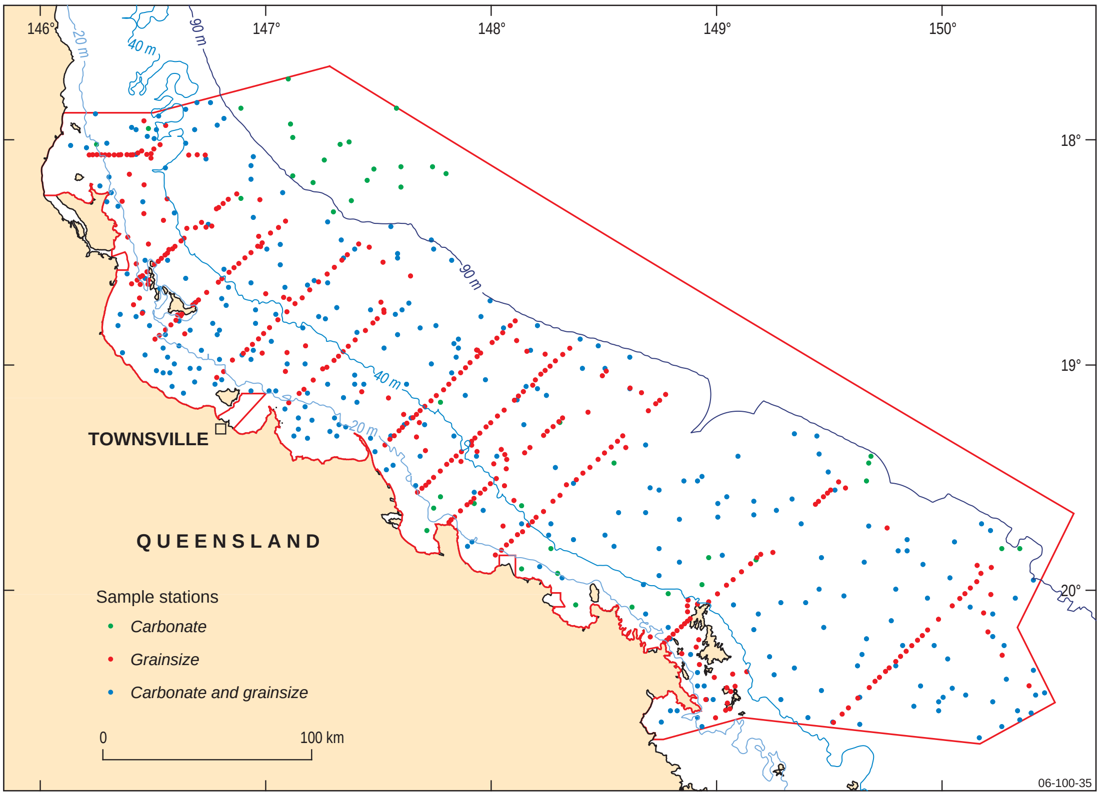

Figure 3.6. Sample stations across the shelf, within the Townsville/Whitsunday Management Area of the GBR Marine Park. Stations where: a) carbonate; b) grainsize; and c) both carbonate and grainsize samples were collected, with divisions between the inner, middle and outer shelves shown with blue lines.

3.3.2.2. General processing procedure

Quantitative sediment attribute data was verified and imported into ArcGIS 9.1 in comma separated value (csv) format. Data were gridded around reefs and the coast, to the boundary of the Marine Park and then clipped to reduce artefacts. The bathymetry of the 20 m (inner), 40 m (middle) and 90 m (outer) isobaths was contoured to identify the major shelf divisions. A shapefile of these isobaths was created for statistical analysis. Statistical analysis of sediment attribute data was undertaken on the geomorphic features dataset, the major shelf divisions and GBRMPA planning zones.

3.3.2.3. Data analysis and presentation

Sediment data were processed and gridded in ArcGIS 9.1 using the Spatial Analyst extension. All maps were created, compiled and exported from ArcGIS 9.1. quantitative sediment data was interpolated to raster using: a) inverse distance weighted interpolator (used due to the distribution of the sample data); b) approximate cell size of 0.01 decimal degrees (dd) (~ 1 km); c) a search radius (maximum interpolation distance from a point) of approximately 20 kilometres (0.2 decimal degrees) and; d) the maximum number of surrounding points considered (extrapolation distance), was 12. The boundaries of the coast and reefs were used as 'Barrier Lines' during the griding process to better reflect the effect of these boundaries on sediment distribution. Samples within the reefs were excluded from the analysis (Table 3.2). To reduce artefacts that were inconsistent with the surrounding data points due to interpolator extrapolation, additional clip areas were

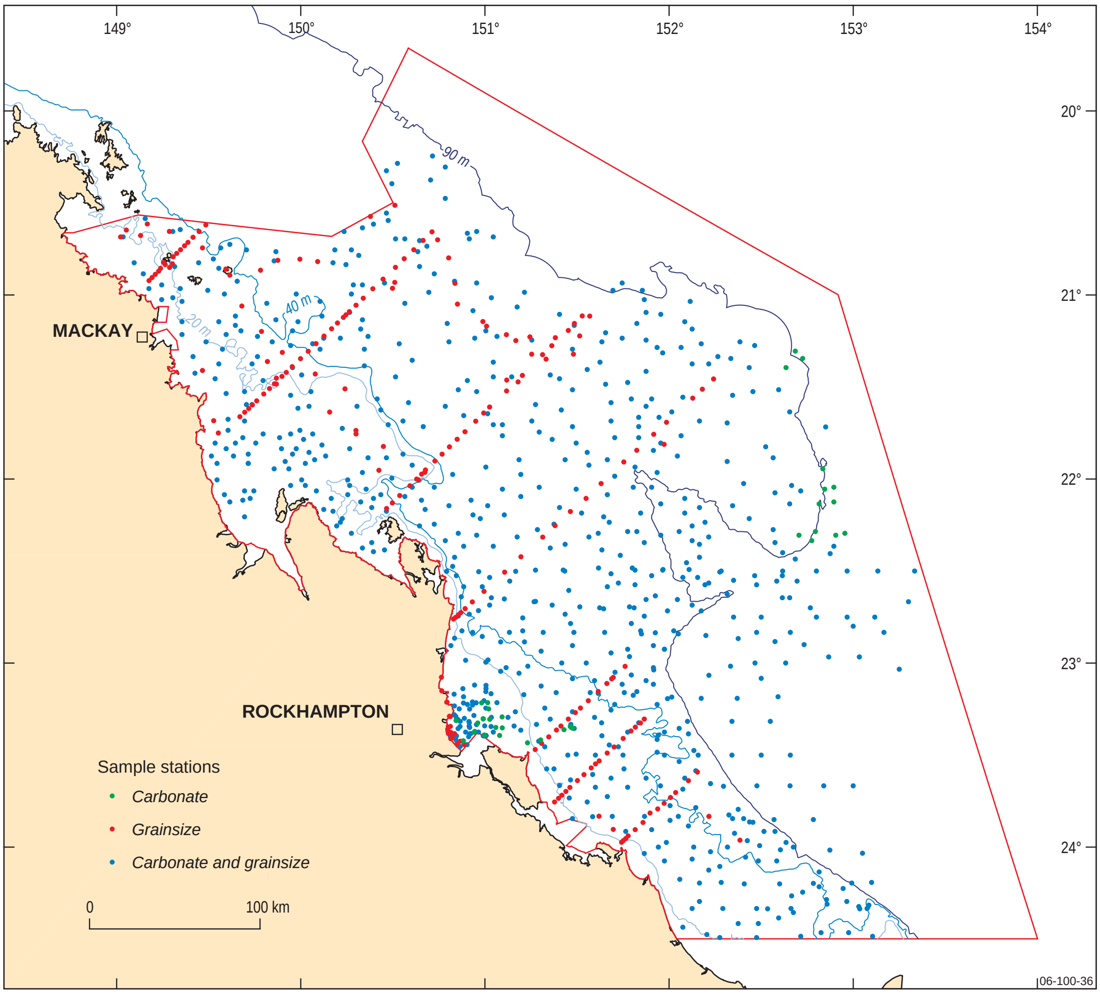

Figure 3.7. Sample stations across the shelf, within the Mackay/Capricorn Management Area of the GBR Marine Park. Stations where: a) carbonate; b) grainsize; and c) both carbonate and grainsize samples were collected, with divisions between the inner, middle and outer shelves shown with blue lines.

added to the Marine Park boundary. Contours were generated from the Grids using the Spatial Analyst extension in ArcGIS 9.1. A smoothing process was applied during generation to obtain the final lines. The resulting grids were then classified in 20 percent ranges for display and analysis purposes.

Table 3.2. Number of samples and stations that occur on reefs, and were therefore, not included in the gridding of sediment attributes.

Seabed region	Samples			Stations		
	AIMS	Other	All	AIMS	Other	All
Inner shelf	0	10	10	0	9	9
Middle shelf	20	134	154	20	54	74
Outer shelf	3	7	10	3	1	4
Continental slope	0	6	6	0	1	1
Total	23	157	180	23	65	88

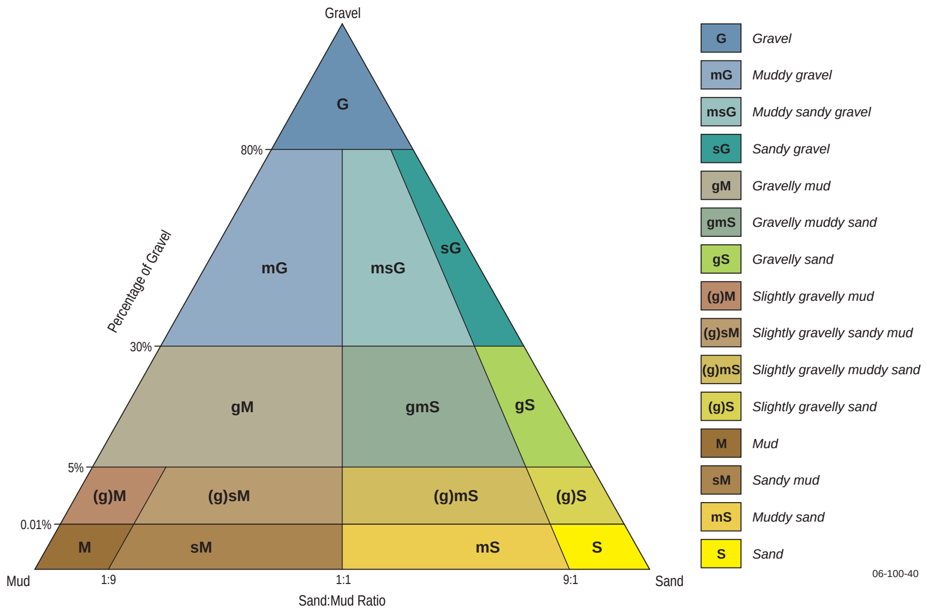

Figure 3.8. Triangular diagram of the Folk (1954) textural classification scheme.

Statistical analysis of the sediment grids used converted ESRI Shape files based on 20 percentile groupings. These shape files were then intersected with the Geomorphic Features dataset, the shelf division's dataset and the planning zone area dataset, and the resultant kilometre and percentage areas calculated.

3.3.2.3. Data accuracy and reliability

The statistical analyses were based on a quantitative sediment data from a high sample resolution (density) which produces a comprehensive distribution over the entire GBR province (Fig 3.8). These consistent sediment sampling strategies and analysis together make for a reliable and accurate dataset of the sediments occurring within the GBR Marine Park.

The sediment attribute data used in this report were sourced from the MARS database. These data has previously undergone strict quality control processes and has been validated against corporate standards that maintain the database. Data sourced from MARS are robust and therefore comprise a reliable dataset for characterising the seabed. The availability of public data from the MARS database must comply with Geoscience Australia's terms of data use, which requires an agreement with external parties from which the data are supplied.

3.3.3. Geomorphic Features Data

The total seabed area of each of the planning zones differed for the statistical analysis of the area of sediments and geomorphic features, to more accurately reflect the coverage and seabed area of each dataset within the seven planning zones. Statistical analysis of the sediment grids was based on the inter-reefal seabed area of each planning zone, which excludes the area of reefs from the total (Table 3.3). Due to the occurrence of reefs in the Geomorphic Features dataset, statistical analysis of the geomorphic features was based on the total seabed area of the planning zones, including the reefs (Table 3.3).

Table 3.3. The seabed areas of planning zones used in statistical calculations.

Planning zones	***Total seabed area**		**+Inter-reefal seabed area**	
	Kilometre^2	*Percent*	*Kilometre^2*	*Percent*
Scientific Research	150	0.04	80	0.03
Preservation	710	0.20	480	0.15
Conservation Park	5,160	1.49	4,370	1.34
Buffer	9,890	2.86	9,880	3.04
Habitat Protection	97,250	28.17	85,620	26.37
Marine National Park	114,490	33.16	108,350	33.37
General Use	116,540	33.76	115,930	35.70

* For geomorphic features
+ With reefs excluded, for sediments

4. Inter-reefal sedimentology

This chapter provides the most up-to-date assessment of inter-reefal seabed sediments on the shelf and slope in the GBR Marine Park. This is the first quantitative spatial analysis of sediment texture and composition in the GBR using new regional data. By characterising seabed sediments, we provide insights into the physical processes controlling sediment grainsize, composition and distribution, which can be used as a monitoring tool to predict changes to sedimentary environments. This information can also be used to help characterise inter-reefal habitats and to infer seabed biodiversity.

4.1. SURFACE SEDIMENTS

The character and spatial distribution of sediments vary in the GBR Marine Park in relation to water depth. Sediment samples were recovered from inter-reefal areas on each part of the shelf and slope (Fig. 1.3). We describe the regional sedimentary characteristics of each of part of the shelf and slope, based on the division of the continental shelf into three separate regions (e.g. inner shelf: 0-20 m, middle shelf: 20-40 m, and outer shelf: 40-90 m) by previous workers (e.g. Belperio, 1983; Maxwell, 1968). Surface sediments are described in terms of their texture and composition and mapped using GIS. **Surface sediment maps for %gravel, %sand, %mud, %bulk carbonate, %carbonate sand and %carbonate mud are shown in Appendix A (pp 99-122).**

4.1.1. Marine Park

The grain size of surface sediments varies across the Marine Park region, with changes observed between the continental shelf and the continental slope. Generally, sediments on the shelf comprise relatively low amounts of gravel and mud, and high amounts of sand (Table 4.1, Appendix A). This differs from the continental slope, which contains less gravel and sand than the shelf and higher mud concentrations.

Folk Classification:— The Marine Park is dominated by gravelly muddy sands, gravelly sands and slightly gravelly muddy sands (e.g. Folk, 1954) (Figs. 3.8 and 4.1; Appendices A-F). Gravelly muddy sand (gmS) covers 48,030 km^2 (14.6%) of the total Marine Park area and occurs across the inner, middle and outer parts of the shelf (Appendix F). It is the most common on the landward side of the reefs on the middle shelf, and is less common on the outer shelf and in southern parts of the MP offshore Gladstone. Gravelly sand (gS) covers 44,230 km^2 (13.5%) of the MP and occurs across the shelf, but is the most common on the outer shelf and continental slope. It frequently occurs on the inner, middle and outer shelf in the southern regions, offshore Gladstone. Slightly gravelly muddy sand ((g)mS) covers 44,010 km^2 (13.4%) of the total MP area and occurs across the shelf, but is most common on the middle and outer shelves. Muddy gravel (mG), slightly gravelly mud ((g)M) and sand (S) are the least common sediment textures, covering 560 km^2 (0.2%), 1,100 km^2 (0.4%) and 1,160 km^2 (0.3%) of the in the MP area, respectively.

Texture:— The gravel fraction is generally low across the Marine Park and has a patchy spatial distribution with localised areas of high gravel concentration (Fig. 4.1). Mean gravel concentrations are 14, 11 and 12% on the inner, middle and outer shelf, respectively, and the mean gravel concentration of the slope is 11% (Table 4.1). Low gravel concentrations of <20% dominate the shelf, covering between 76 and 87% of each part of the shelf (Fig. 4.2, 4.3, 4.4).

Mean sand concentrations are 59, 67 and 67% on the inner, middle and outer shelf respectively, and 53% on the slope (Table 4.1). Only a few regions on the shelf have sand concentrations of <20%, which generally correlate with mud contents of >80% (Appendix A). Regions of <20% sand cover 4% of the total inner shelf area, and 1.9% and 1.8% of the middle and outer shelves, respectively (Figs. 4.2-4.4).

Mean mud concentrations are 27, 22 and 20% on the inner, middle and outer shelf respectively, and is 36% on the slope (Table 4.1). On the inner shelf, mud concentrations of >80% cover 2.6% of the total area of the inner shelf. On the middle and outer shelf mud concentrations of >80% cover only 0.8% and 0.9% of each shelf area (Figs. 4.3 and 4.4).

Overall, inner shelf sediments contain higher amounts of gravel and mud than the middle and outer shelves, whereas sand occurs in its lowest concentration (Table 4.1). Middle shelf sediments contain high amounts of sand, which is comparable to the outer shelf, moderate mud contents and the lowest gravel content overall. Outer shelf sediment contains the highest sand concentrations and the lowest mud contents compared with the inner and middle shelves, and moderate gravel contents. Continental shelf sediments contain relatively higher sand and gravel concentrations, and lower mud concentrations, compared to the continental slope (Figs. 4.2- 4.5).

Composition:— The composition of surface sediments changes within the Marine Park, as carbonate concentrations increase across the shelf and with proximity to reefs. Bulk carbonate, carbonate sand and carbonate mud concentrations generally increase eastward across the shelf (Appendix A,).

Mean bulk carbonate concentrations are 37, 55 and 78% on the inner, middle and outer shelves respectively (Table 4.2). Bulk carbonate concentrations of >80% cover 133 km^2 (0.4%) of the inner shelf, 13,475 km^2 (22.2%) of the middle shelf and 56,673 km^2 (55.8%) of the outer shelf. Relatively high mean bulk carbonate concentrations on the outer shelf reflect the increasing dominance of carbonate sediments in inter-reefal areas around the reefs. The across-shelf increase in bulk carbonate continues on the continental slope, where mean bulk carbonate concentrations are 73% and are relatively similar to those on the outer shelf (Table 4.2). High carbonate concentrations on the middle and outer shelf correspond with high sand concentrations (Appendix A). Areas of low bulk carbonate (<40%) occur

Table 4.1. Sediment grain size statistics for each region.

Region	Statistics	Gravel %	Sand %	Mud %
Inner Shelf	*Min:*	0	1	0
	Max:	94	100	99
	Mean:	14	59	27
	Std Dev:	15	21	23
Middle Shelf	*Min:*	0	5	0
	Max:	94	100	93
	Mean:	11	67	22
	Std Dev:	11	20	19
Outer Shelf	*Min:*	0	0	0
	Max:	97	100	100
	Mean:	12	67	20
	Std Dev:	14	19	19
Continental Slope	*Min:*	0	1	0
	Max:	97	99	99
	Mean:	11	53	36
	Std Dev:	21	25	28

infrequently on the outer shelf, and occur in the form of patchy carbonate concentrations on the shore proximal parts of the outer shelf offshore Townsville and Yeppoon, within areas of higher (>60%) concentrations.

Carbonate sand and carbonate mud concentrations also increase across the shelf. Mean carbonate sand concentrations increase from 44% on the inner shelf to 80% on the outer shelf, and mean carbonate mud concentrations increase from 24% on the inner shelf to 72% on the outer shelf (Table 4.2). The continental slope contains relatively high overall carbonate concentrations. On the continental slope, mean carbonate sand and carbonate mud concentrations are 85% and 72%, respectively (Table 4.2).

Across-shelf changes in carbonate concentration produce a shelf-parallel zonation, which is quite pronounced in the central shelf (offshore Cairns, Townsville and Mackay), and becomes more complex/indistinct south of Rockhampton. Bulk carbonate contents of <20% dominate on the inner shelf, covering an area of 7,320 km^2 (20%) (Fig 4.2). This corresponds with mud concentrations of >80%, which cover 930 km^2 (3%) of the inner shelf, 470 km^2 (1%) on the middle shelf and 900 km^2 (1%) on the outer shelf. Low overall bulk carbonate concentrations on the inner shelf indicate dominantly terrigenous compositions. Sediments with relatively high mud concentrations (>60%) in some parts of the middle and outer shelf correspond to lower (40-60%) and variable bulk carbonate concentrations. Such an area occurs offshore Cooktown, and extends for approximately 300 km past Cairns. Overall, the highest carbonate concentrations of >80% occur within the outer reef tract and on the continental slope.

Overall, inner shelf sediments contain the lowest bulk carbonate, carbonate sand and carbonate mud concentrations (Table 4.2). Middle shelf sediments contain intermediate amounts of bulk carbonate, carbonate sand and carbonate mud concentrations. Outer shelf sediments contain the highest overall bulk, sand-fraction and mud-fraction carbonate concentrations. Continental shelf sediments contain bulk carbonate concentrations slightly lower than those occurring on the outer shelf, and relatively higher carbonate sand and carbonate mud concentrations.

Table 4.2. Sediment composition statistics for each region.

Region	Statistics	Carbonate Bulk %	Carbonate Sand %	Carbonate Mud %
Inner Shelf	*Min:*	0	1	0
	Max:	97	94	77
	Mean:	37	44	24
	Std Dev:	19	24	12
Middle Shelf	*Min:*	0	1	0
	Max:	100	95	89
	Mean:	55	57	47
	Std Dev:	26	27	20
Outer Shelf	*Min:*	2	2	0
	Max:	100	100	95
	Mean:	78	80	72
	Std Dev:	18	19	19
Continental Slope	*Min:*	0	1	0
	Max:	99	98	93
	Mean:	73	85	72
	Std Dev:	14	16	18

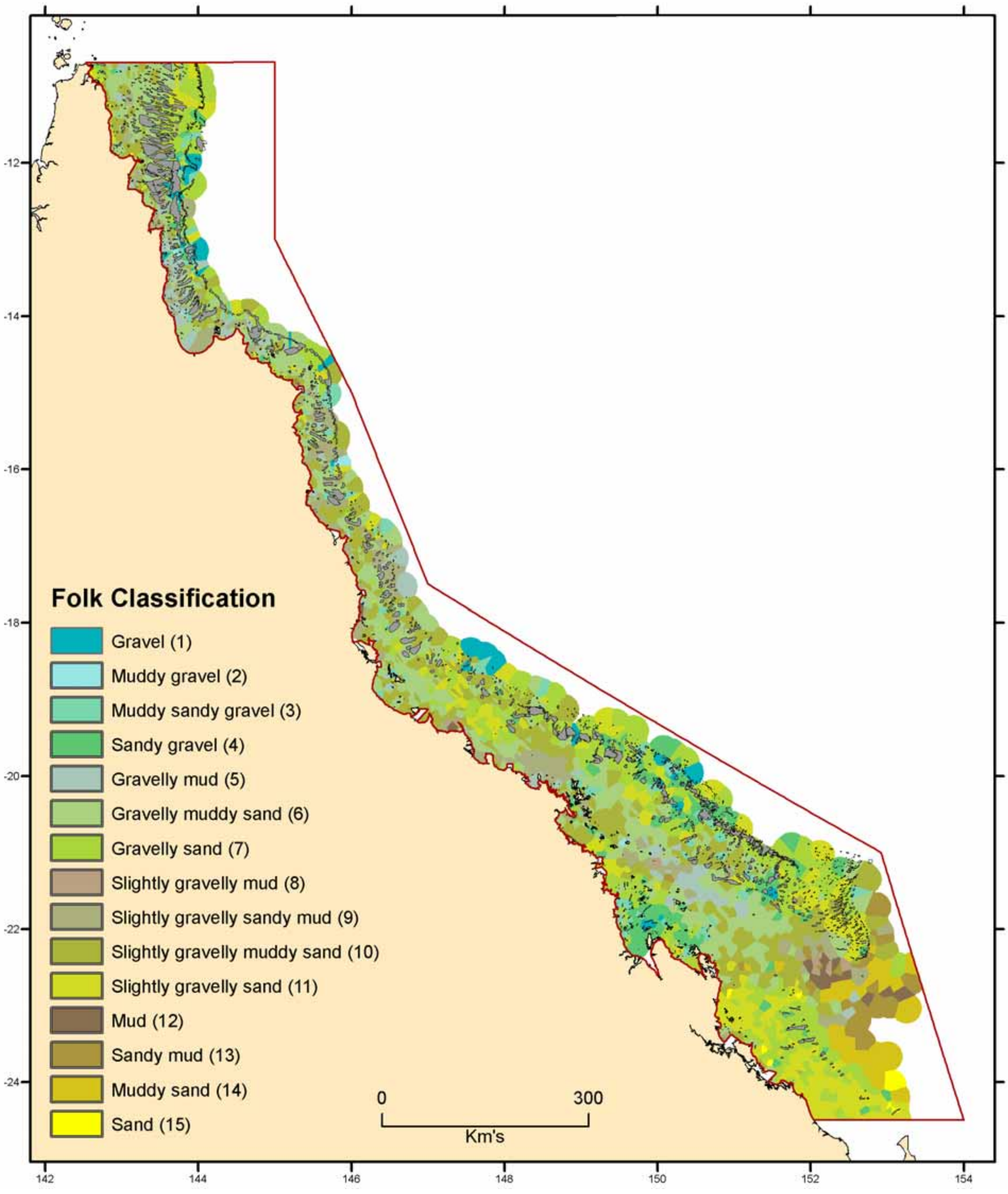

Figure 4.1. Map of the distribution of sediment textures within the Marine Park using the Folk (1954) classification scheme.

4.1.2. Inner Shelf (0-20 m)

Surface sediments on the inner shelf are distinguished by relatively high terrigenous mud concentrations and relatively low carbonate concentrations (Fig. 4.2). Mud concentrations of >60% generally occur within 50 km of the coast and in the majority of north-facing embayments. These areas are also characterised by relatively low carbonate concentrations of <40%, reflecting supply of siliciclastic grains from local rivers. Generally, surface sediments on the inner shelf are low in carbonate concentrations that increase with distance from the coast, river mouths and north facing embayments, producing a general shelf-parallel zonation.

Folk Classification:— Inner shelf sediments are a combination of muds, sandy muds and muddy sands, sands and gravelly sands (i.e. Folk, 1954) (Figs. 3.8; 4.6 and 4.7). Gravelly muddy sand (gmS) is the most dominant sediment type on the inner shelf, and covers 34,970 km² (10.7%) of the total inner shelf region (Appendix B). These sediment types are the most extensive in near shore areas, river mouths and next to islands (Fig. 4.1). Slightly gravelly muddy sand ((g)mS), slightly gravelly sand ((g)S) and slightly gravelly sandy mud ((g)sM), also occur in high quantities, and cover 22,180 km² (6.8%), 14,050 km² (4.3%), and 10,110 km² (3.1%), respectively.

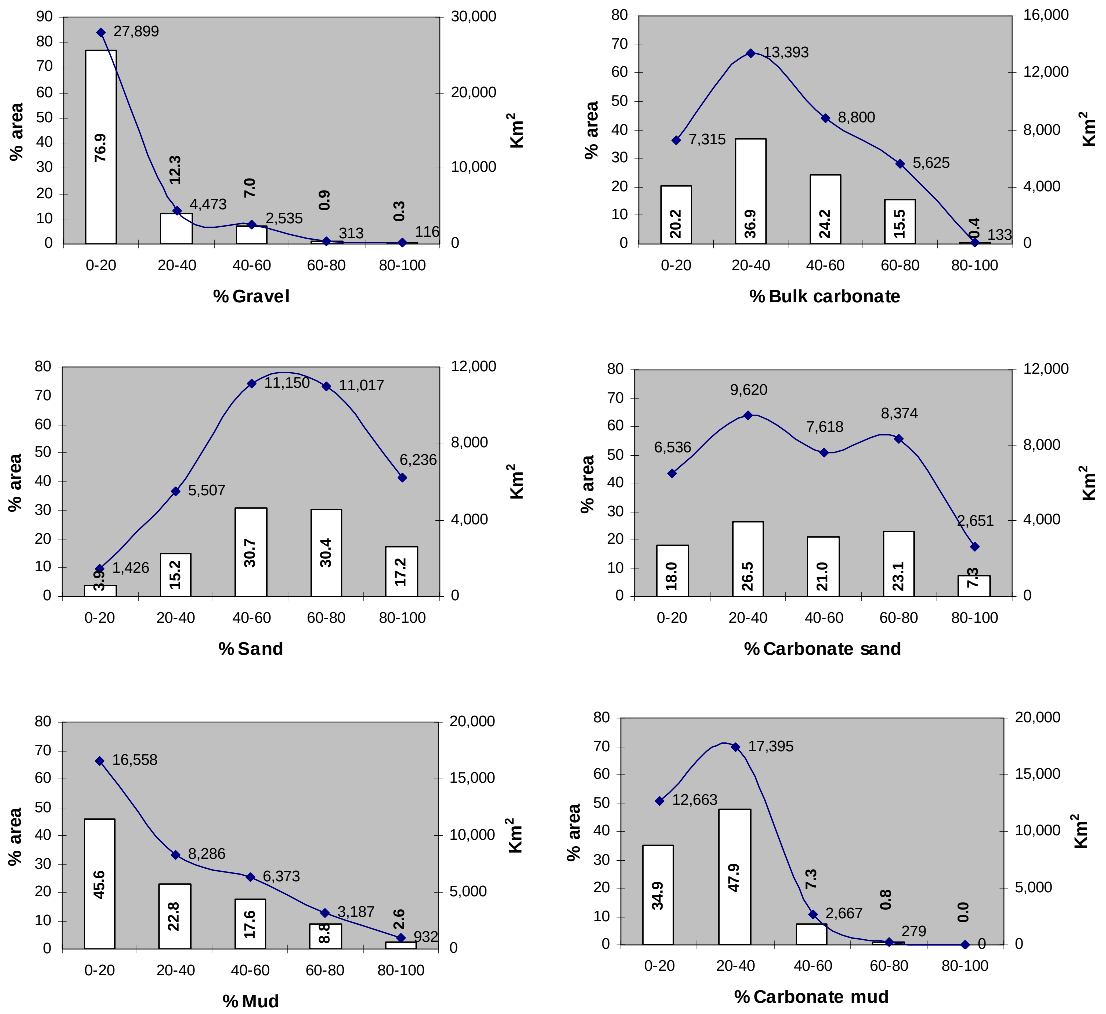

Figure 4.2. Histograms of the percentage area covered by different concentrations of gravel, sand, mud, bulk carbonate, carbonate sand and carbonate mud, in inter reefal areas on the inner shelf. Bars = percent; lines = km^2.

These facies occur in exposed nearshore environments, next to headlands and areas on the open shelf (Fig. 4.2). Gravel (G) sediments are less common and cover 390 km² (<1%) of the inner shelf, occurring near reef shoals and exposed tidal areas. Sand (S) sediments cover 210 km² (<1%) and occur in the nearshore, coastal and intertidal areas. Mud (M) sediments cover 270 km² (<1%) and occur in near shore areas, including near river mouths.

Texture:— Inner shelf sediments contain relatively high concentrations of mud and sand and relatively low gravel concentrations. Gravel concentrations on the inner shelf range from 0% to 94% and have a mean of 14% (Fig. 4.2; Table 4.1). High gravel concentrations of >60% form locally and cover 430 km² (1.2%) of the total area of the inner shelf (Fig. 4.2). These local high gravel concentrations produce patchy distributions, such as those observed in Broad Sound (<70%) and offshore Mackay (20-40%). These relatively high gravel concentrations are generally associated with high carbonate concentrations and relatively low sand concentrations.

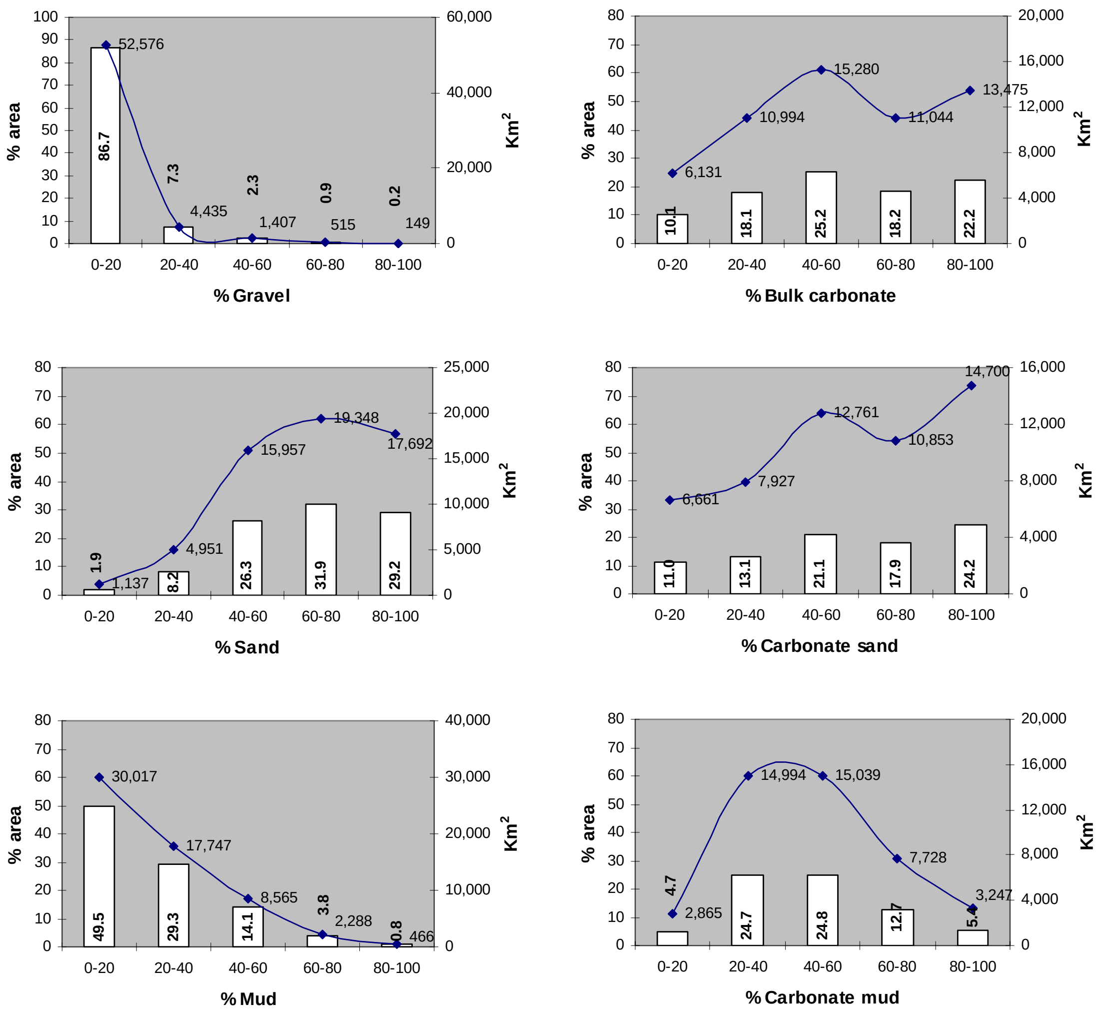

Figure 4.3. Histograms of the percentage area covered by different concentrations of gravel, sand, mud, bulk carbonate, carbonate sand and carbonate mud, in inter reefal areas on the middle shelf. Bars = percent; lines = km².

Sand concentrations range from 1% to 100% with a mean of 59% (Fig. 4.2, Table. 4.1). Sand concentrations of >80% cover 6,240 km² (17%) of the inner shelf, with the most extensive areas occurring in southern parts of the Marine Park offshore Mackay, Rockhampton and Gladstone. Sand concentrations of <20% cover 1,430 km² (4%) of the inner shelf (Fig. 4.2), and principally occur in Princess Charlotte Bay and near Cape Bowling Green (Appendix A). Inner shelf regions with relatively high sand concentrations also have relatively low gravel and mud concentrations.

Mud concentrations range from 0% to 99% and have a mean of 27% (Table 4.1). Mud concentrations of >60% cover 4,120 km², or more than 10% of the inner shelf (Fig. 4.2). Mud concentrations of >80% occur in north-facing embayments such as Princess Charlotte Bay, Lockhart River and Cape Bowling Green (Appendix A). Concentrations of <20% cover 16,560 km² (46%) of the inner shelf, with concentrations of <5% occurring along northern parts of Cape York and along much of the shelf south of Mackay (Fig 4.2). These areas

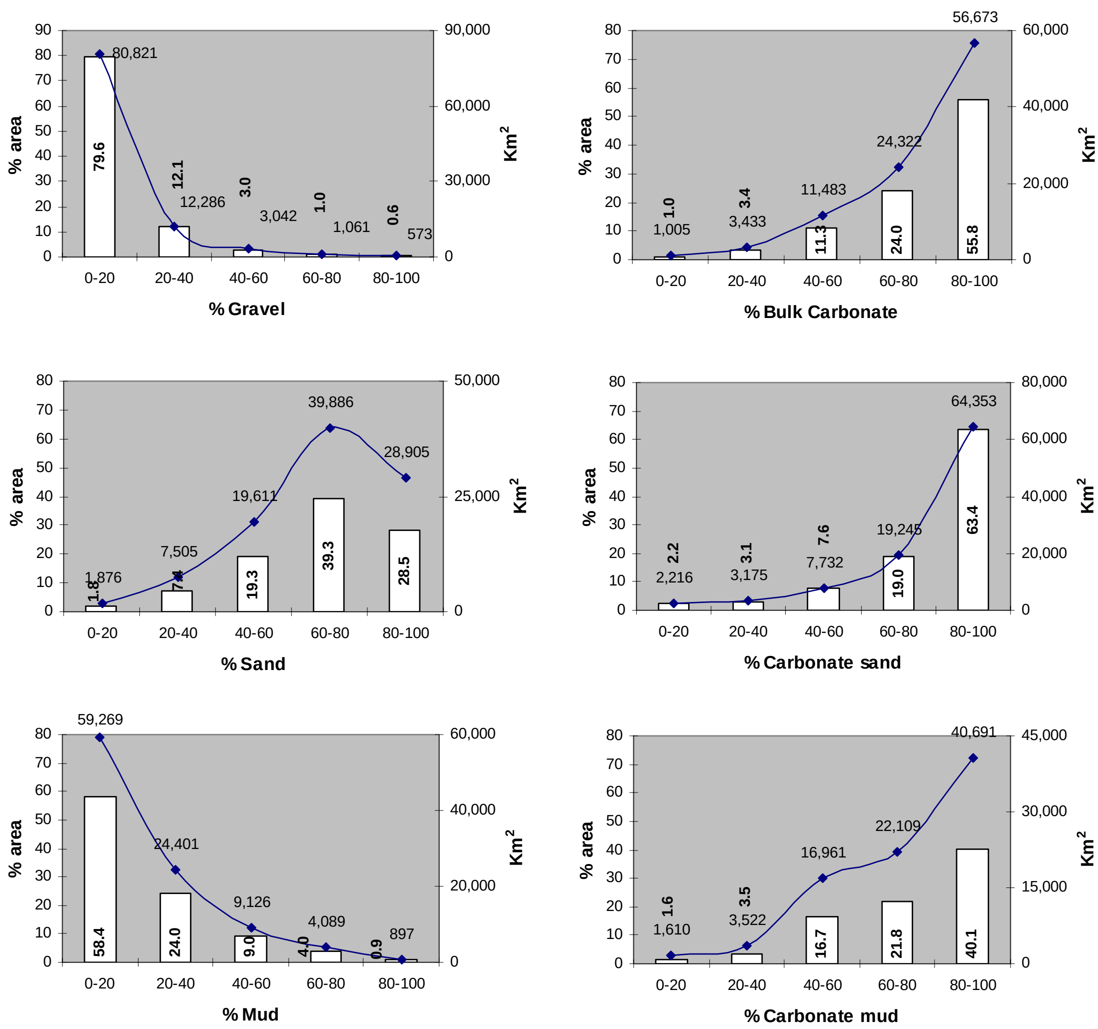

Figure 4.4. Histograms of the percentage area covered by different concentrations of gravel, sand, mud, bulk carbonate, carbonate sand and carbonate mud, in inter reefal areas on the outer shelf. Bars = percent; lines = km^2.

correspond to areas of high sand concentration. In Broad Sound, mud concentrations are <10% and occur with relatively high gravel concentrations of <70%.

Examples of the distinctive grain size distributions for four environments can be recognised on the inner shelf (Fig. 4.8). The sediment distributions are bimodal for A, B and C, have negatively skewed populations and represent exposed near shore environments around islands and headlands. Example D displays a relatively symmetrical distribution and represents an environment influenced by fluvial inputs, such as occurs near river mouths and in north-facing embayments. Example A sediments in exposed open shelf/headland environment are characterised by fine to coarse sand, and a minor component of mud. This sample has a standard deviation of 208.51 μm, reflecting the bimodal distribution and very poorly sorted sample (Appendix C). Example B sediments in the inter- island/near shore environment are characterised by fine to very coarse sand, and

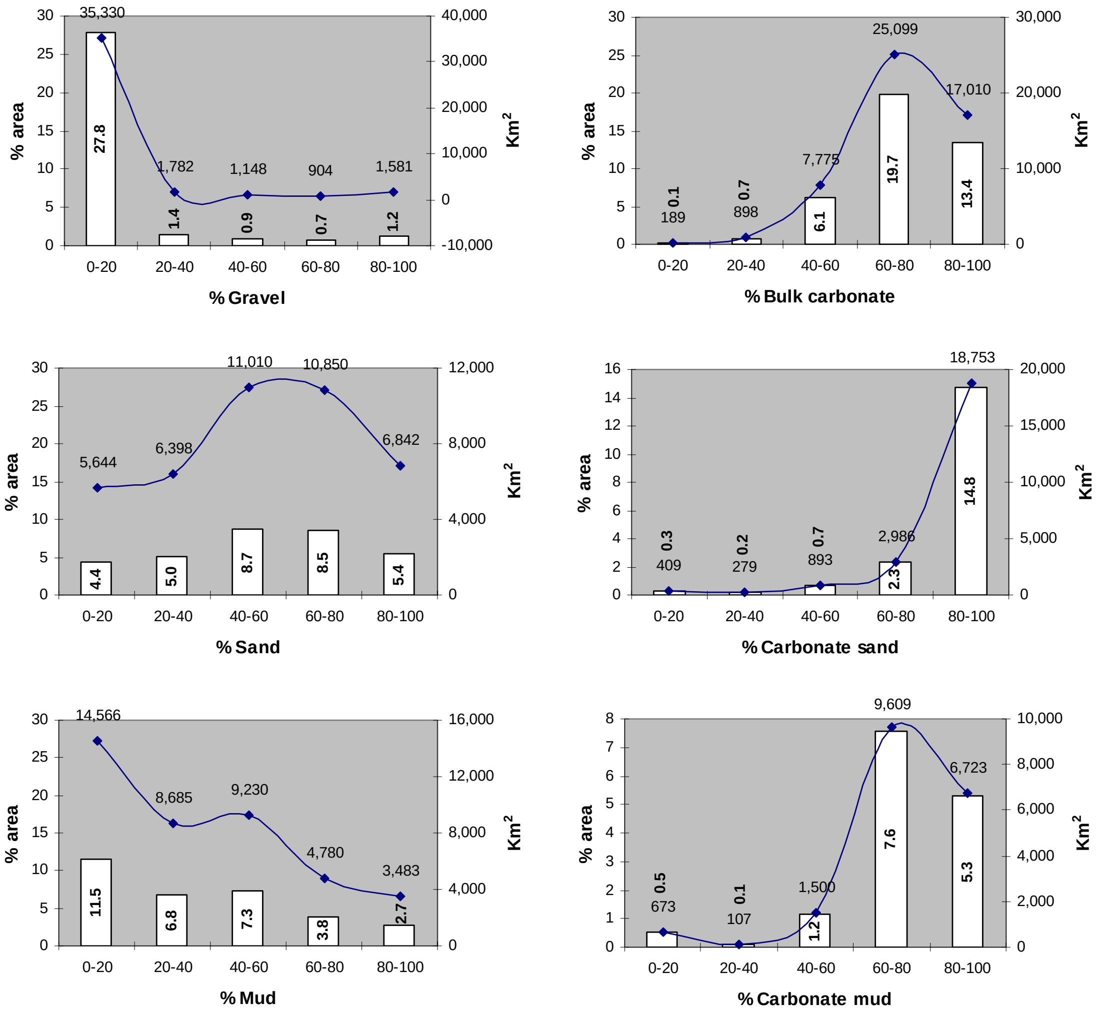

Figure 4.5. Histograms of the percentage area covered by different concentrations of gravel, sand, mud, bulk carbonate, carbonate sand and carbonate mud, in inter reefal areas on the continental slope. Bars = percent; lines = km^2.

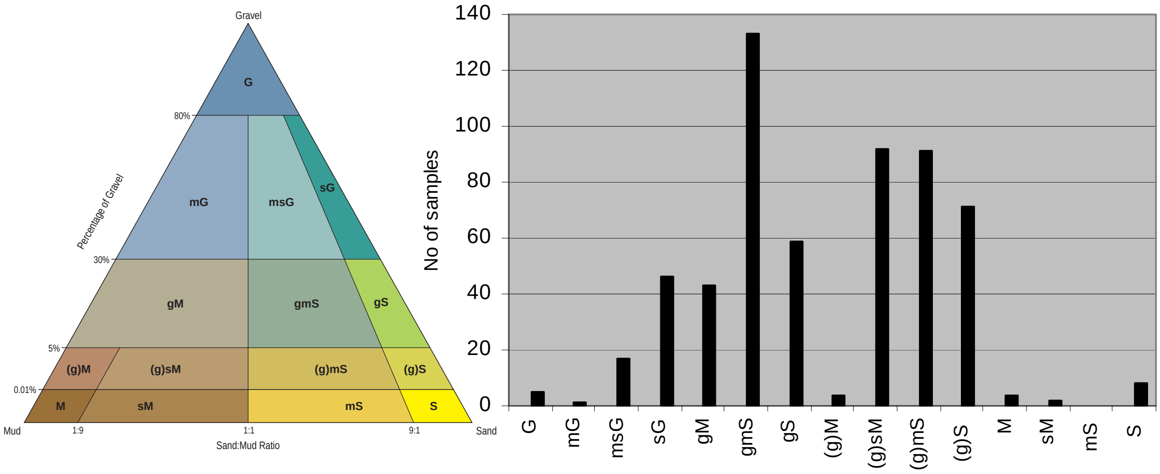

Figure 4.6. Histogram of the textural characteristics of inner shelf sediments, using the Folk (1954) classification scheme.

a significant mud component. This sample has a standard deviation of 465.59 µm, which reflects a trimodal distribution and a very poorly sorted sample (Appendix C). Example C sediments in the open shelf environment are characterised by muddy to sandy sediments and low amounts of the gravel fraction. This sample has a standard deviation of 67.26 µm, sediments in a near shore/river outflow environment are characterised by clay to very fine sand. This sample has a standard deviation of 16.64 µm, reflecting a unimodal population and very well sorted sample (Appendix C).

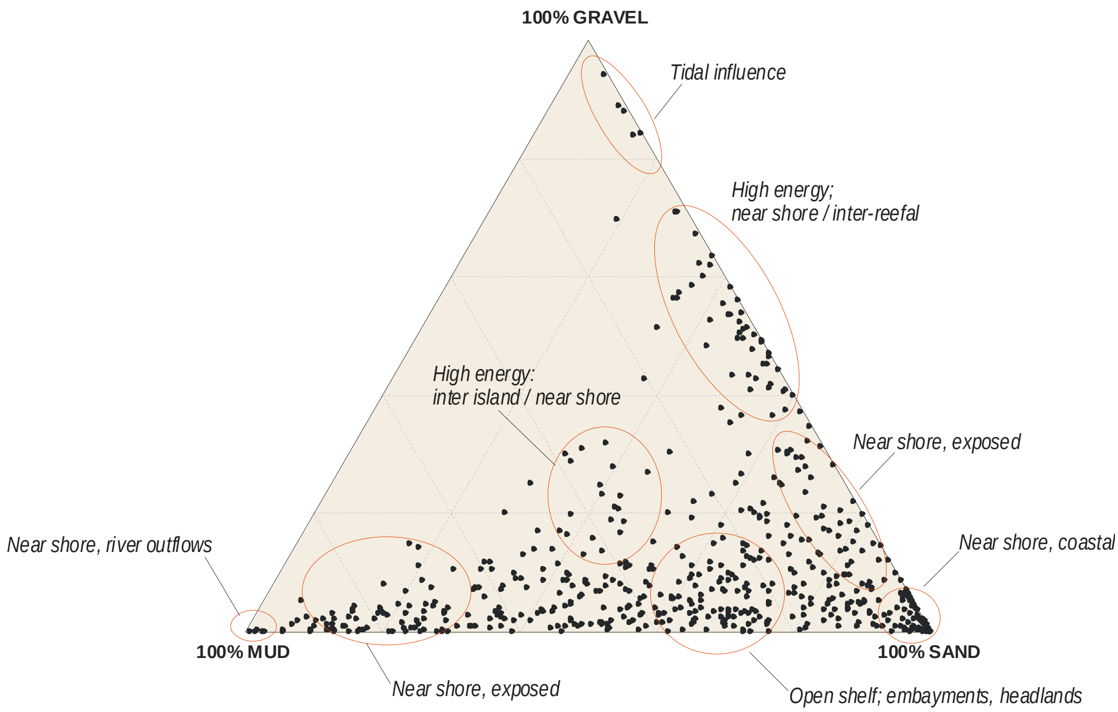

Figure 4.7. Ternary diagram showing the textural characteristics and associated environments of inner shelf sediments.

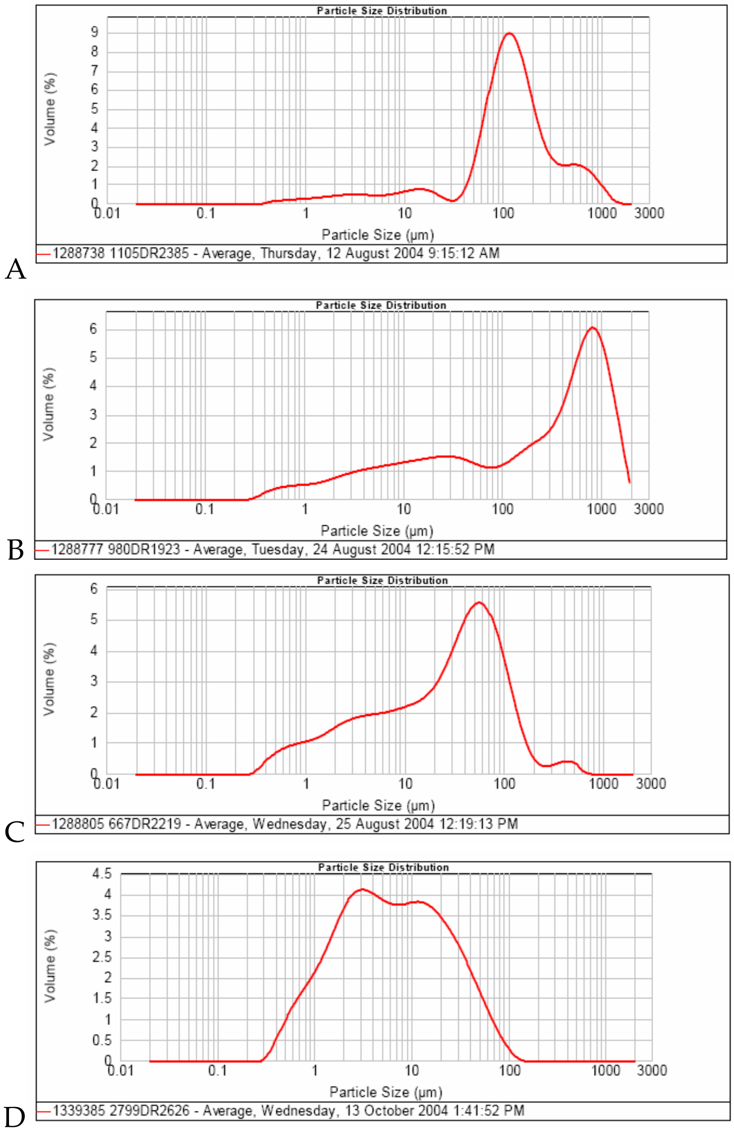

Figure 4.8. Common grain size distribution plots of inner shelf sediments; (a) sample 1288738 from the exposed headland environment near Cape Sandwich on the east coast of Hinchinbrook Island, in the Townsville-Whitsunday Management Area, (b) sample 1288777 from the inter-island / near shore environment near the Howick Group, in the Far Northern Management Area, (c) sample 1288805 from the open shelf environment offshore Cairns, in the Cairns-Cooktown Management Area, and (d) sample 1339385 from the near shore north-facing embayment environment west of Cape Bowling Green, in the Townsville-Whitsunday Management Area.

Composition:— The inner shelf is generally characterised by the lowest carbonate concentrations of the entire GBR shelf (Fig. 4.2). Sediment distribution patterns are influenced by terrigenous sediment supply and dispersal from rivers. Bulk carbonate concentrations range from 0% to 97%, and have a mean of 37% (Table. 4.2). Bulk carbonate concentrations of <40% cover 20,710 km^2 (57%) on the inner shelf (Fig. 4.2). Overall, the trend is an eastward increase in carbonate concentrations across the shelf. Concentrations of between 10 and 20% generally occur within 50 km of the coast, but extend up to 80 km from the coast south of Gladstone and increase to between 60 and 70% towards the middle shelf. Bulk carbonate concentrations of >60% cover 5,760 km^2 (16%) of the inner shelf and occur in Broad Sound (60-80%) and nearby coastal fringing reefs east of Cape York, where concentrations attain 90%.

Mean carbonate sand and mud concentrations reach 44% and 24%, respectively. Together with low bulk carbonate concentrations, these contents reflect a significant siliciclastic fraction. Carbonate sand concentrations of <20% cover 6,540 km² (18%) of the total area of the inner shelf (Fig 4.2). Carbonate sand concentrations of <10% occur near Cape Bowling Green and offshore Mackay. Low carbonate mud concentrations of <20% cover 12,660 km² (35%) of the inner shelf and form a continuous shelf parallel band, approximately 610 km in length, from Cape Flattery to Cape Upstart.

4.1.3. Middle Shelf (20-40 m)

Surface sediments on the middle shelf are characterised by relatively high sand concentrations and moderate carbonate concentrations. This region is influenced by terrigenous sediment inputs from the inner shelf and carbonate from the outer shelf. Shallow, shore-proximal parts of the middle shelf contain relatively high terrigenous concentrations, whereas deeper, shore-distal parts contain relatively high carbonate concentrations. Sand concentrations attain >80% occur offshore Cape York and offshore Rockhampton (Appendix A). Overall, sand concentrations across the entire middle shelf are relatively similar to those on the outer shelf (Figs. 4.3 and 4.4).

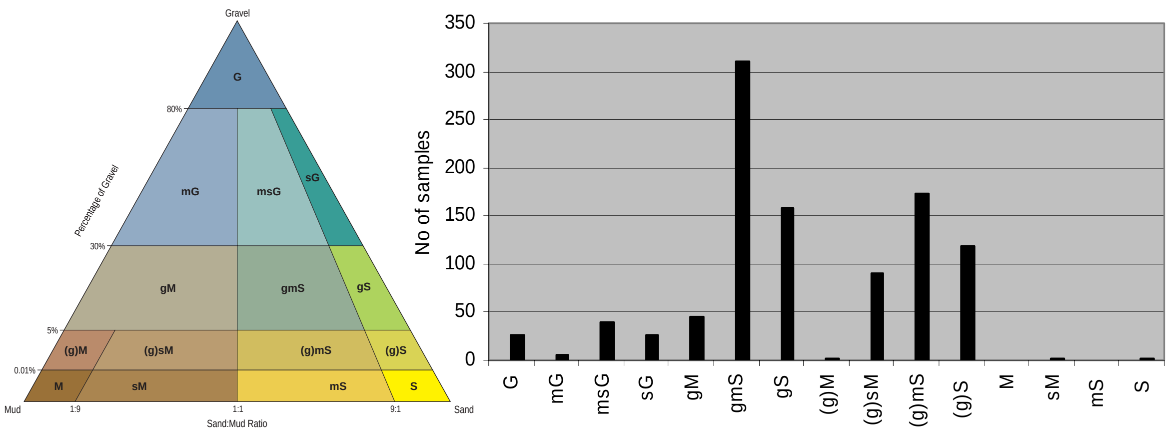

Figure 4.9. Histogram of the textural characteristics of middle shelf sediments, using the Folk (1954) classification scheme.

Folk Classification:— Middle shelf sediments are gravelly, to slightly gravelly sands, muddy sands, and sands (Figs. 3.8 and 4.1). Gravelly muddy sand (gmS) is the dominant sediment type on the middle shelf, and covers 36,960 km² (11.3%) of the area (Figs. 4.9 and 4.10; Appendix B). This sediment type is associated with inter-reefal areas and open, more exposed parts of the shelf away from reefs, such as landward of the ribbon reefs in the far north (Fig. 4.1). Slightly gravelly muddy sand ((g)mS), gravelly sand (gS) and slightly gravelly sand ((g)S) are also relatively extensive, covering 27,650 km² (8.4%), 23,530 km² (7.2%) and 18,890 km² (5.8%) of the total area of the middle shelf (Appendix B). These sediment types occur on open shelf environments and in inter reefal areas. In particular, the slightly gravelly sand sediments dominate on the open shelf offshore Gladstone, and gravelly sand covers a total area of ~60 km² near the Capricorn-Bunker reefs (Fig. 4.1). Gravel (G) covers 2,300 km² (0.7%) of the total middle shelf area and occurs proximal to reefs.

Texture:— Middle shelf sediments contain relatively high concentrations of sand and relatively low gravel and mud concentrations compared with the other shelf regions (Figs. 4.2-4.4). Gravel concentrations on the middle shelf generally range from 0 to 94% and have a mean of 11% (Table 4.1). Gravel concentrations of <20% cover 52,580 km² (87%) of the total area of the middle shelf. Concentrations of >60% are uncommon and cover only 660 km² (1%) of the middle shelf (Fig. 4.3). High gravel concentrations occur locally, such as offshore Temple Bay in the far north (Appendix A). Here, a locally restricted gravel-rich region (>90%) occurs next to the outer barrier reefs and protected shoals.

Sand concentrations range from 5 to 100%, with a mean of 67% (Table. 4.1). Sand concentrations of >60% cover 37,040 km² (61.1%) of the middle shelf and occur seaward of the ribbon reefs in the far north and offshore Rockhampton in the south (Fig. 4.3; Appendix A, E). Sand concentrations of >95% occur near the southern Marine Park boundary. Sand concentrations of <40% cover 6,090 km² (10%) of the middle shelf (Fig. 4.3). Regions of low sand concentration (<40%) form isolated patches in several areas that range in size from <10 km², up to >50 km² where they extend onto the inner shelf. Such areas include offshore Cape Weymouth, south of Cooktown, Bobardt Point and Edgecumbe Bay (Appendix A).

Mud concentrations range from 0 to 93%, with a mean of 22% (Table 4.1). Mud concentrations of <40% dominate the middle shelf region and cover 47,760 km² (79%) of the total area of the middle shelf. Mud concentrations of <20% cover 30,020 km² (50%) of the middle shelf and occur offshore Townsville and south of Mackay (Appendix A, E). Mud concentrations of >80% cover 470 km² (1%) of the middle shelf (Fig. 4.4), with the highest concentrations occurring offshore of Cooktown. These locations have concentrations comparable to those observed north of Cape Grenville and offshore Lockhart River.

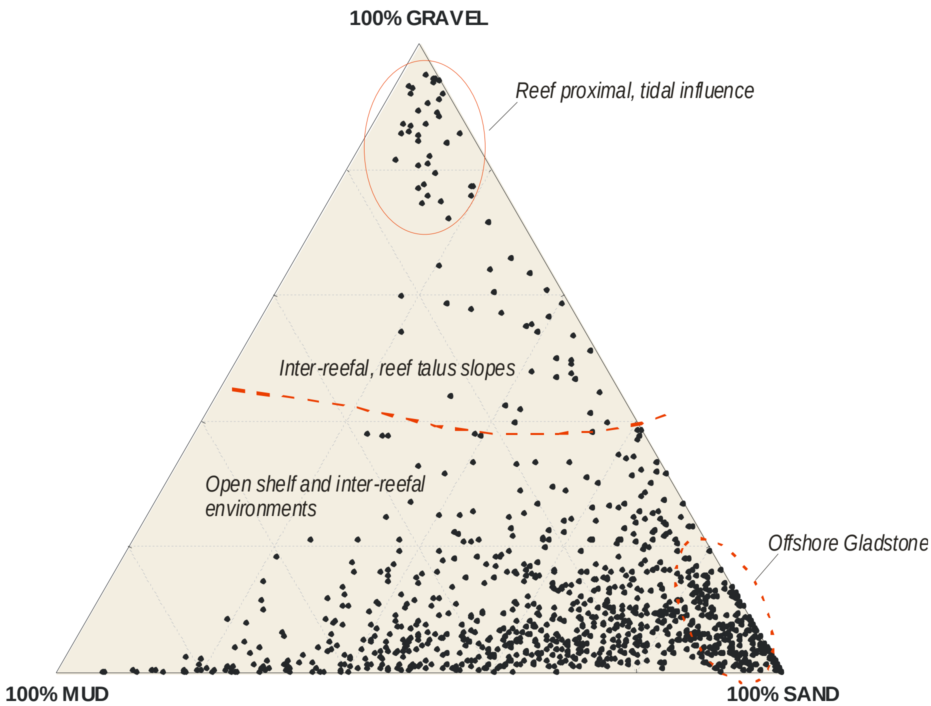

Figure. 4.10. Ternary diagram showing the textural characteristics and associated environments of middle shelf sediments.

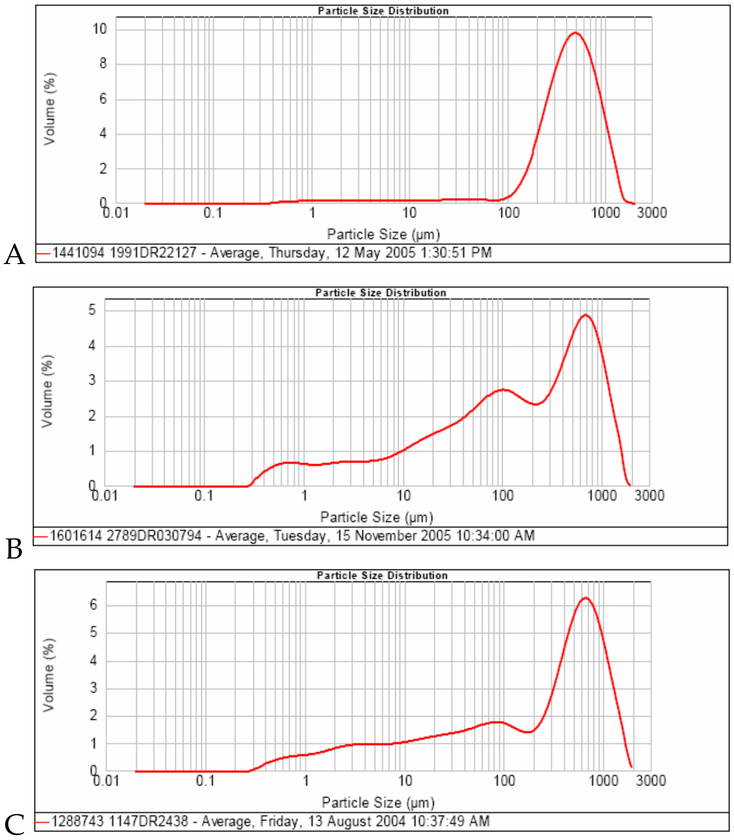

Figure 4.11. Common grain size distribution plots of middle shelf sediments: (a) sample 1441094 from the open shelf/inter-reefal environment, from the Mackay-Capricorn Management Area; (b) sample 1601614 from reef proximal environments, in the Far Northern Management Area; and (c) sample 1288743 from the inter-reefal environments, from the Townsville-Whitsunday Management Area.

Examples of distinctive grain size distributions for three environments can be recognised for middle shelf sediments (Fig. 4.11). Overall the curves represent negatively-skewed unimodal distributions which represent inter-reefal open shelf environments, to bimodal distributions which represent reef proximal and inter-reefal environments. Example A sediments in the open shelf inter-reefal environment are characterised by fine to coarse sand. This sample has a standard deviation of 296.03 µm and unimodal distribution, which reflects moderate to well sorting (Appendix C). Example B sediment in reef proximal environments are characterised by fine mud to coarse sand. This sample has a standard deviation of 382.28 µm and a bimodal distribution, reflecting a moderately well sorted sample (Appendix C). Example C sediment in inter-reefal environments are characterised by fine to coarse sand and mud. This sample has a standard deviation of 415.61 µm and trimodal distribution, reflecting a very poorly sorted sample (Appendix C). In general, middle shelf sediments range from well to poorly sorted and are dominated by the sand fraction.

Composition:— Surface sediments on the middle shelf contain moderate carbonate concentrations, and are a mixture of siliciclastic and calcareous grains. Sediments generally display a shore parallel zonation, which becomes indistinct on parts of the relatively narrow middle shelf south of Mackay, which reaches ~500 m at its narrowest point.

Bulk carbonate concentrations range from 0 to 100%, and have a mean of 55% (Table 4.2). Bulk carbonate concentrations of >80% cover 13,480 km^2 (22%) of the middle shelf, and concentrations of <20% cover 6,130 km^2 (10%) (Fig. 4.3, Appendix E). Inshore parts of the middle shelf off Cairns and Innisfail have a bulk carbonate concentrations of 20-40%. Bulk carbonate concentrations are lowest on the southern parts of the middle shelf south of Gladstone, where bulk, sand and mud carbonate concentrations are <20% (Appendix A). The lowest bulk carbonate concentrations of 2-7% occur north of Hervey Bay, around Lady Elliot Island. Towards the middle shelf reefs, bulk, mud and sand carbonate concentrations are all between 60 and 80% and are the highest for the middle shelf (Appendix A). Bulk, sand and mud carbonate concentrations all increase in the inter-reefal areas, and near reefs in the far north and the Capricorn Group in the south (Appendix A). For example, near Salamander and Mason Reefs in the far north carbonate sand values attain 91% and 93%, and carbonate values of >80% occur nearby mid shelf reefs, off Cape York.

Carbonate sand concentrations range from 1 to 95% and have a mean of 57% (Table 4.2). Carbonate sand concentrations of >60% cover 25,550 km^2 (42%) of the middle shelf and exhibit a high amount of spatial variability (Fig 4.3). Carbonate sand concentrations of <40% cover 14,590 km^2 (24%) of the middle shelf and form local patches of low carbonate sand concentrations in some regions, such as around the Whitsundays and off Mackay, reflecting abrupt changes in the distribution of carbonate sand grains (Appendix A). Carbonate sand concentrations <50% occur offshore Capes Grenville, Melville, Flattery and Bowling Green, reflecting an increase in siliciclastic grains at these locations. A broad area of low carbonate sand concentrations of 1-7% occurs north of Hervey Bay.

Carbonate mud concentrations range from 0 to 89% and have a mean of 47% (Table 4.2). Carbonate mud concentrations of <40% cover 17,860 km^2 (29%) of the total area of the middle shelf (Fig 4.3, Appendix E). South of Cape Flattery, the strong across-shelf zonation in bulk composition is revealed by the carbonate mud concentrations, which are relatively low inshore (<40%) and high (60-80%) around the middle shelf reefs. Carbonate mud concentrations of >60% cover 10,9780 km^2 (18%) of the middle shelf (Fig 4.3).

4.1.4. Outer Shelf (40-90 m)

Outer shelf sediments are characterised by relatively low mud and gravel concentrations and relatively high carbonate concentrations (Fig. 4.4). The sand fraction is spatially abundant (>80%), and this produces a patchy distribution across the outer shelf. High concentrations of bulk carbonate, carbonate sand and carbonate mud dominate, and are mainly restricted to the inter-reefal areas around the outer shelf reefs.

Folk Classification:— Outer shelf sediments are mostly gravelly sands to slightly gravelly sands (Figs. 3.8 and 4.1). Slightly gravelly muddy sands ((g)mS) are the most dominant sediment type on the outer shelf, with the highest number of samples (Figs. 4.12 and 4.13). It covers 32,930 km^2 (10%) of the region and generally occur on open shelf environments away from reefs (Appendix B). However, gravelly sand (gS) and gravelly muddy sand (gmS) have the greatest spatial extent, and cover 36,680 km^2 (11.2%) and 34,990 km^2 (10.7%) of the outer shelf, respectively. Gravelly sands occur in the inter-reefal areas around the Swain Reefs and gravelly muddy sands generally occur on the open shelf. Slightly gravelly sand ((g)S) also occurs frequently on the outer shelf and covers an area of 27,070 km^2 (8.3%). Gravel covers 5,540 km^2 (1.7%) of the outer shelf and occurs proximal to locations on the reef tract and at the shelf edge (Appendix B). Mud (M) and sand (S) sediments are not abundant on the outer shelf, covering 1,270 km^2 (0.4%) and 220 km^2 (0.1%) of the outer shelf, respectively, and occur locally near the shelf edge nearby Capricorn Channel (Fig. 4.1).

Texture:— Outer shelf sediments are dominated by relatively high amounts of sand, and relatively low amounts of gravel and mud. Gravel concentrations range from 0% to 97%, with a mean of 12% (Table 4.1). The outer shelf is dominated by gravel concentrations of <20%, which covers 80,820 km² (79%) of the area (Fig. 4.4, Appendix B). Gravel concentrations of >60% cover 1,630 km² (2%) of the outer shelf. Gravel concentrations of >60% occur near the reef tract, such as offshore Townsville, Proserpine and Mackay, where gravel contents attain 97, 92 and 89%, respectively (Appendix A).

Sand concentrations range from 0% to 100% and have a mean of 67% (Table 4.1). More than 60% (68,790 km²) of the outer shelf contains sand concentrations of greater than 60% (Fig. 4.4, Appendix B). Sand concentrations >80% cover 28,905 km² (28.5%) of the outer shelf, and concentrations >90% occur near the Anniversary Group offshore Townsville, the Capricorn Group and Swain Reefs (Appendix A). Sand concentrations of <40% cover 9,380 km² or less than 10% of the outer shelf (Fig. 4.4), and occur offshore of Townsville and Mackay (Appendix A). Areas with <40% sand on the outer shelf, occur in localised patches juxtaposed with regions of relatively high sand concentration. Generally, on the outer shelf high sand concentrations are associated with regions of low mud concentration.

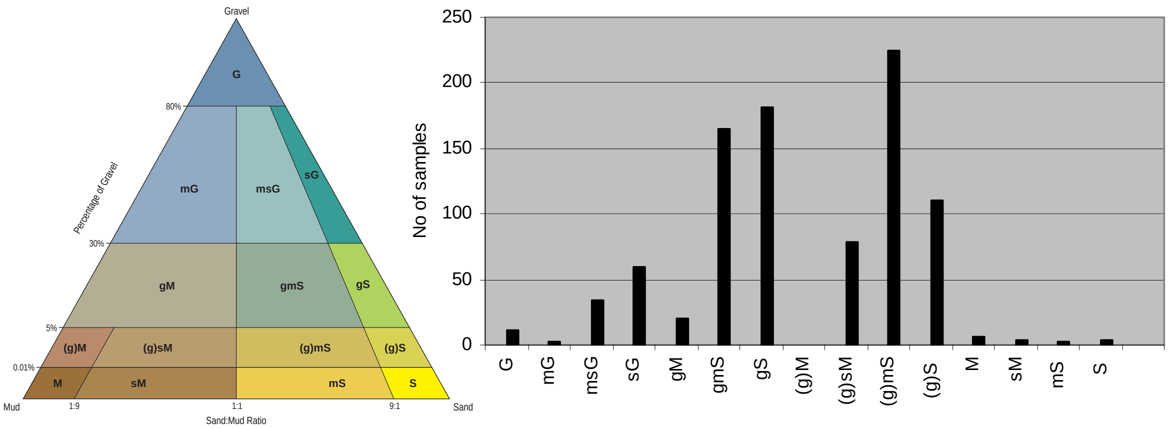

Figure 4.12. Histogram of the textural characteristics of outer shelf sediments, using the Folk (1954) classification scheme.

Mud concentrations range from 0% to 100%, and have a mean of 20% (Table. 4.1). Mud concentrations of <20% dominate on the outer shelf and cover 59,270 km² (58%) of the region (Fig. 4.4, Appendix B). Mud concentrations of >40% cover 14,110 km² (14%) of the outer shelf, and occur as localised concentrations of mud, such as those offshore of Cairns. South of Mackay, a region of relatively high mud forms a shelf-parallel area extending into Capricorn Channel. The highest overall mud concentrations of >90% occurs offshore Mackay and Yeppoon (Appendix A).

Examples of the distinctive grain size distributions for three environments can be recognised in outer shelf sediments (Fig. 4.14). Overall the sediment distributions are bimodal, to unimodal and negatively skewed, which characterise open shelf, inter-reefal and reef proximal environments. Example A sediments in an open shelf environment are characterised by mud to very coarse sand, with a dominant component of fine sand. This sample has a standard deviation of 298.165 μm and bimodal distribution, reflecting a very poorly sorted sample (Appendix C). Example B sediments in a reef proximal environment are characterised by mud and fine to coarse sand. This sample has a standard deviation of 160.735 μm and bimodal distribution, reflecting very poor sorting (Appendix C). Example

C sediments in an inter-reefal environment are characterised by medium sand, and a minor component of mud. This sample has a standard deviation of 348.865 µm and unimodal distribution, which reflects a moderately sorted sample (Appendix C). In general, outer shelf sediments are moderately to poorly sorted and dominated by the sand fraction.

Composition:— Outer shelf sediments contain relatively high carbonate concentrations compared with the inner and middle shelves (Figs. 4.2-4.4). Bulk carbonate concentrations range from 2% to 100%, and have a mean value of 78% (Table 4.2). Bulk carbonate concentrations >60% cover 80,990 km², which is more than 70% of the outer shelf (Fig. 4.4). The highest concentrations of >90% occur proximal to the reefs, such as near the outer barrier reefs in the north offshore Cape York and in the south around Swain Reefs (Appendix A). Away from reefal areas towards the middle shelf, such as east of Townshend Island in the south, bulk carbonate concentrations range between 40 and 80%. Bulk carbonate concentrations of <40% cover only 4,440 km² (4%) of the outer shelf and occur in an isolated patch north of the Capricorn Group (Fig. 4.4; Appendix A).

Carbonate sand concentrations range from 2% to 100%, with a mean of 80% (Table 4.2). Carbonate sand concentrations of >80% cover 64,350 km² (63%) of the outer shelf, suggesting a high input of calcareous grains from the reefs. Near the Swains Reefs, carbonate sand concentrations attain 95%, with carbonate mud concentrations of >90% (Appendix A). Carbonate sand concentrations of <40% cover 5,390 km² (5%) of the outer shelf. Low carbonate sand concentrations of <20% are conspicuous, and form in an isolated patch offshore Yeppoon that covers an area of 2,220 km² (2%) (Fig 4.4).

Carbonate mud concentrations range from 0% to 95%, with a mean of 72% (Table 4.2). Carbonate mud concentrations of >60% cover 62,800 km² (61.8%) of the outer shelf (Fig 4.4).

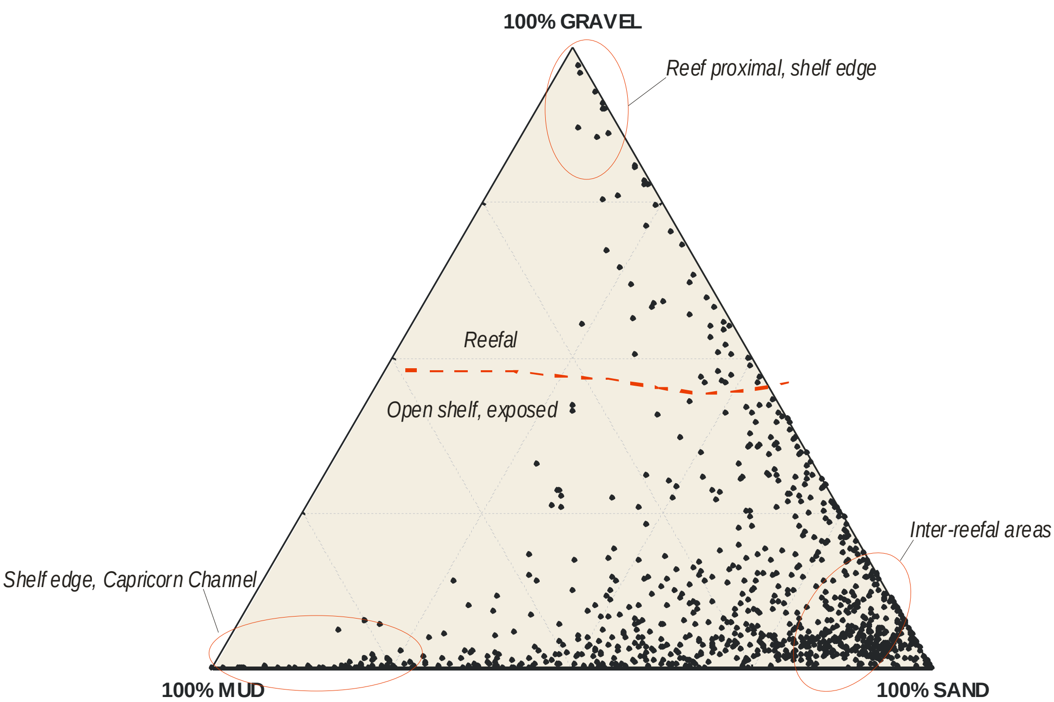

Figure 4.13. Ternary diagram showing the textural characteristics and associated environments of outer shelf sediments.

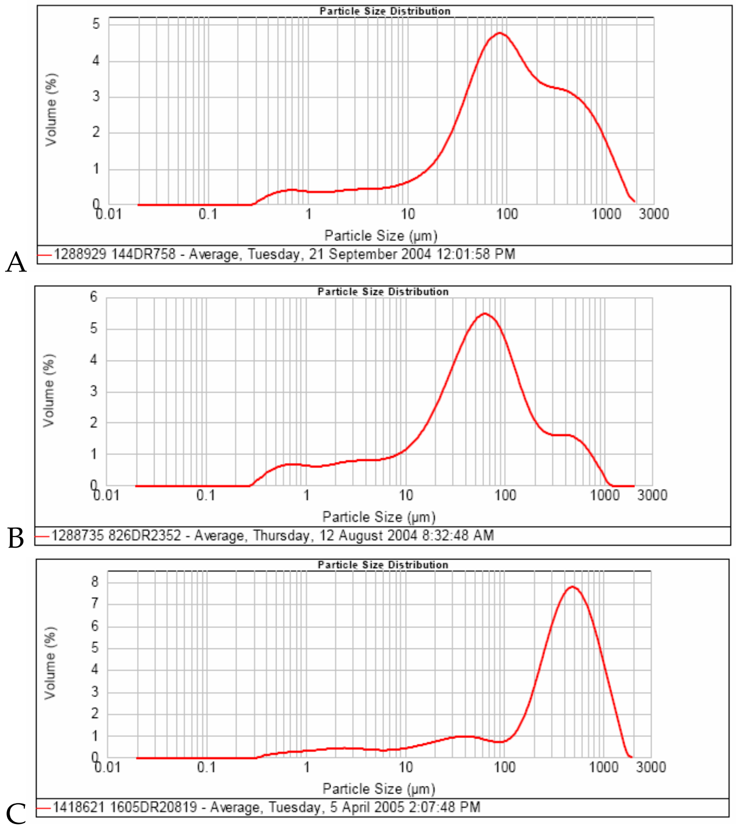

Figure 4.14. Common grain size distribution plots of outer shelf sediments: (a) sample 1288929 from an open shelf environment off Hinchinbrook Island, in the Townsville-Whitsunday Management Area; (b) sample 1288735 from a reef proximal environment off Innisfail, in the Cairns-Cooktown Management Area; and (c) sample 1418621 from an inter-reefal environment in Swain Reefs, in the Mackay-Capricorn Management Area.

Carbonate mud concentrations of <40% cover 5,130 km^2 (5%) of the outer shelf. Concentrations of between 40 and 60% occur offshore of Cooktown and Cairns and produce a patchy carbonate distribution that correlates with relatively high mud concentrations in this area. At this location, bulk carbonate concentrations are variable, ranging from 56 to 91% (Appendix A).

Overall, the highest bulk, sand and mud carbonate concentrations of >80% occur in inter-reefal areas, and increase towards the shelf edge. The across-shelf pattern is evident in low bulk (<60%), sand (<60%) and mud (<40%) carbonate concentrations shore proximal of the outer shelf reef tract. These relatively lower carbonate concentrations are gradational from the middle shelf, where, <50 km from the coast the influence of terrigenous sediments predominates.

4.1.5. Continental Slope (90-~4000 m)

The continental slope within the Marine Park is characterised by relatively high mud concentrations and relatively low sand concentrations, which have patchy spatial distributions (Figs. 4.2-4.5, Appendix A). Carbonate concentrations are generally >60% and areas proximal to the shelf edge generally contain the highest concentrations.

Folk Classification:— Continental slope sediments are mostly sandy muds and muddy sands (Figs. 3.8 and 4.1). Muddy sands (mS) are the most dominant sediment type on the slope, with the highest number of samples, although it only covers 9,010 km^2 (2.7%)

of the total slope area (Figs. 4.15 and 4.16; Appendix E). Muddy sand occurs over a range of water depths, from 100 to 500 m (Fig. 4.1). Gravelly sand (gS) is the most spatially extensive and covers an area of 26,210 km² (8%) of the continental slope. Sandy mud (sM) also occurs frequently, covering 6,100 km² (1.9%) and occurs on the upper slope and in the deeper parts of Capricorn Channel, at <350 m. Slightly gravelly sandy mud ((g)sM) is also common and covers 7,170 km² (2.2%) mainly in Capricorn Channel. Gravel (G) sediment occurs on the upper continental slope, off Townsville and covers 4,410 km² (1.3%) (Appendix E). Sand (S) occurs in isolated patches offshore Gladstone, south east of Swain Reefs and Lady Elliot Island, covering an area of 720 km² or less than 1% of the area. Mud (M) occurs at a range of water depth and many samples cluster in central Capricorn Channel, covering a total area of 2,250 km² (0.7%).

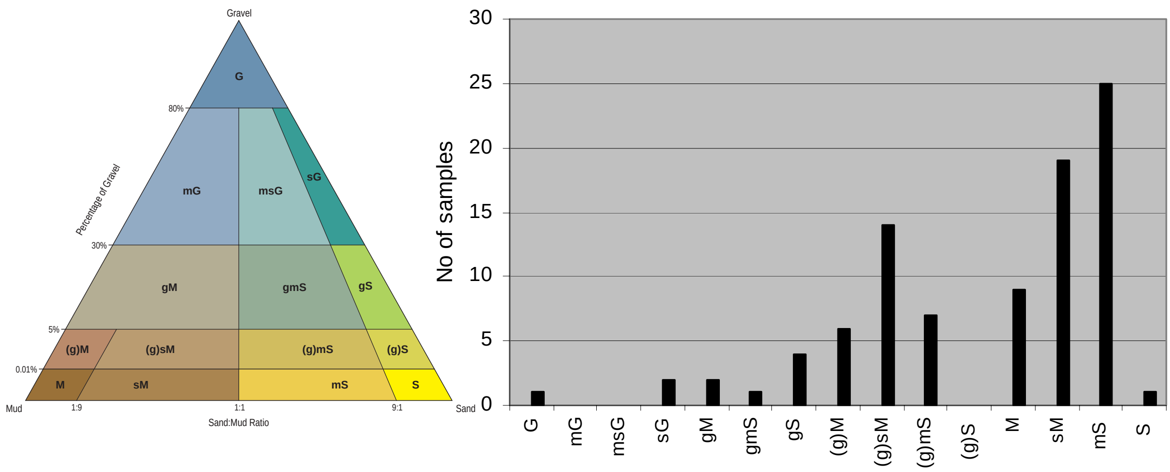

Figure 4.15. Histogram of the textural characteristics of continental slope sediments, using the Folk (1954) classification scheme.

Texture:— Continental slope sediments are dominated by relatively high sand and mud concentrations, and relatively low gravel concentrations (Fig 4.5). Gravel concentrations range from 0% to 97%, with a mean of 11% (Table 4.1). Concentrations of <20% dominate and cover 35,330 km² (28%) of the area (Fig 4.5, Appendix E). Gravel concentrations of >60% cover 2,490 km² (2%) of the slope. Concentrations of 22% and 44.5% occur on the upper slope at <100 metres water depth, and correlate with high bulk carbonate contents at these locations.

Sand concentrations range from 1% to 99% and have a mean of 53% (Table. 4.1). Sand concentrations of >60% cover 17,690 km² (14%) of the slope and attain 85% at the shelf edge, east of the Capricorn Group (Appendix A). Sand concentrations range from 3.2 to 86% over a distance of <25 km on the slope and produce patchy distributions near Capricorn Channel. Sand concentrations of <20% cover 5,640 km² (4%) of the area, and attain 1.4% at ~100 metres water depth in Capricorn Channel. On the continental slope, low sand concentrations correspond to areas with high mud concentration.

Mud concentrations range from 0% to 99%, with a mean of 36% (Table. 4.1). Mud concentrations of <20% dominate the slope and cover 14,570 km² (11%) of the area, occurring below the shelf break (Fig 4.5, Appendix E). Mud concentrations of >80% cover 3,480 km² (3%) of the total area of the continental slope and occur in the Capricorn Channel and in an isolated location offshore Cairns, and correspond to high mud concentrations on the outer shelf (Appendix A).

Examples of the distinctive grain size distributions for three environments can be recognised in continental slope sediments (Fig 4.17). The sediment distributions are unimodal and bimodal, and are dominated by negatively skewed populations, which characterise the channel and upper slope environments. Example A sediments from the Channel environment (i.e. Capricorn Channel) are characterised by mud and very fine sand. This sample has a standard deviation of 21.15 μm and a unimodal distribution, which reflects a very well sorted sample (Appendix C). Example B sediments in the upper slope environment are characterised by fine sand and a minor component of mud. This sample has a standard deviation of 106.50 μm and a bimodal distribution reflecting very poor sorting (Appendix C). Example C sediments from the channel environment are characterised by mud and sand. This sample has a standard deviation of 75.95 μm and a bimodal distribution, which reflects very poor sorting. In general, continental slope sediments range from very well sorted to very poorly sorted and are dominated by mud and sand.

Composition:— Continental slope sediments are characterised by relatively high overall carbonate concentrations (Fig. 4.5). Bulk carbonate concentrations range from 0 to 99%, with a mean of 73% (Table 4.2). Bulk carbonate concentrations of >60% cover 42,110 km² (33%) of the slope, and concentrations >80% cover 17,010 km² (13.3%) (Fig. 4.5, Appendix E). Areas with >80% carbonate concentration have a localised distribution near the shelf edge and south east of the Swain Reefs. Bulk carbonate concentrations of <40% cover 1,090 km² (1%) of the slope, and form patches of low carbonate sediment (Fig. 4.5; Appendix A). A ~50 km² region of low bulk carbonate (<40%) near Capricorn Channel is associated with high (>60%) mud concentrations. Offshore of Cooktown and Cairns, bulk

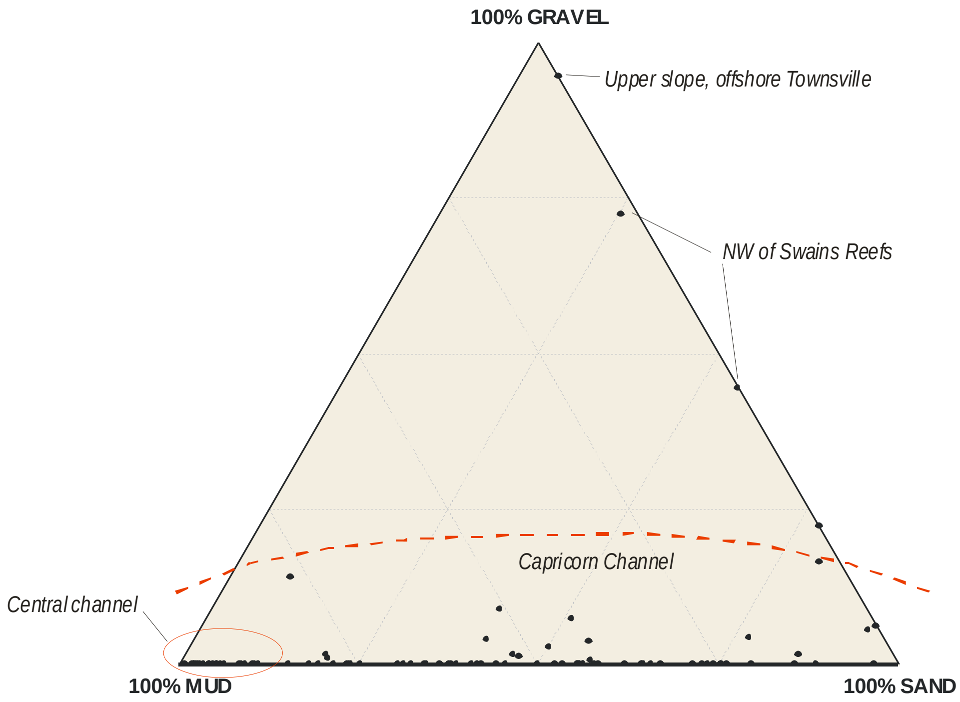

Figure 4.16. Ternary diagram showing the textural characteristics and associated environments of continental slope sediments.

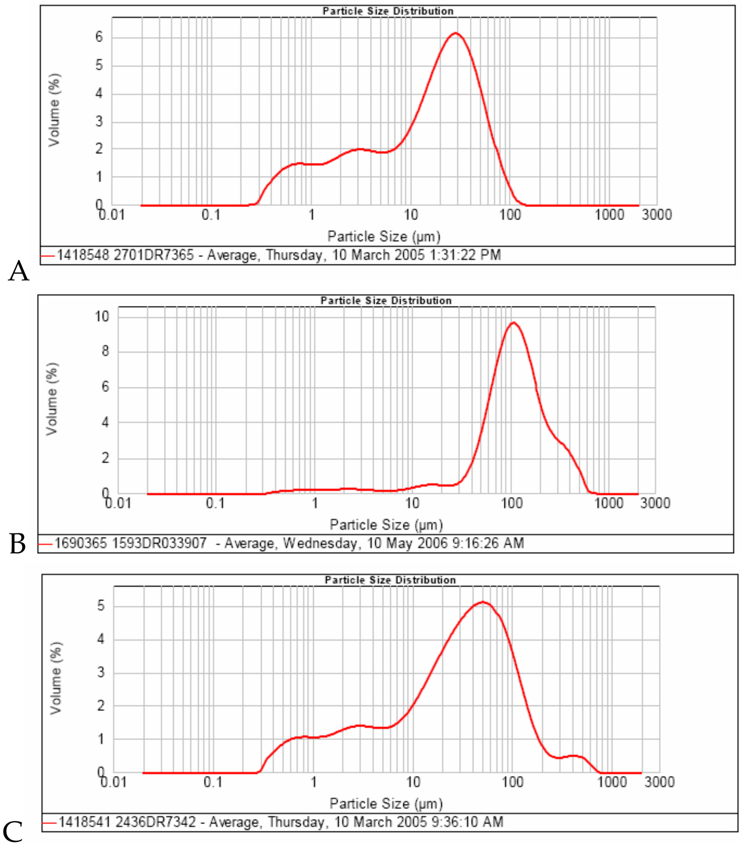

Figure 4.17. Common grain size distribution plots of continental slope sediments: (a) sample 1418548 in ~100 m water depth in Capricorn Channel; (b) sample 1690365 in <100 m water depth north east of Swains Reefs; and (c) sample 1418541 in ~150 m water depth SE of Capricorn Channel, from the Mackay Capricorn Management Area.

carbonate concentrations have a patchy distribution and increase from <40% near the shelf break, to 60-80% in the deeper water (~400 m) (Appendix A).

Carbonate sand concentrations range from 1 to 98%, and have a mean of 85% (Table 4.2). Carbonate sand concentrations of >80% cover 18,750 km² (15%) of the slope (Fig. 4.5, Appendix E). Regions with high bulk and sand carbonate concentrations have patchy distributions along the slope, which may be influenced by changes in the composition of shelf sediments. Carbonate sand concentrations of <40% cover 690 km² (<1%) of the slope and occur as local patches near the shelf edge (at 90 m water depth) north of Hervey Bay (Appendix A).

Carbonate mud concentrations range from 0 to 93%, and have a mean of 72% (Table 4.2). Carbonate mud concentrations of >60% cover 16,330 km² (13%) of the slope, and are restricted to the upper slope in water depths of 100-200 m (Fig 4.5, Appendix E). Overall, the continental slope is dominated by bulk, sand and mud carbonate concentrations greater than 60%, and in many areas carbonate sediments display patchy spatial distribution patterns (Appendix A).

5. Application to the Marine Park Authority planning zones

The sedimentology results (Chapter 4) together with existing data about the geomorphic features, compiled by Harris et al. (2005), provide two comprehensive physical datasets from which to characterise the seabed in the GBR Marine Park (MP). These datasets present a detailed means of assessing the physical substrate and nature of the seabed. Quantitative analysis of the coverage and percentage area of these datasets gives a robust method to compare and contrast the characteristics of each zone. This provides managers and planners with baseline information about the seabed, to asses any correlations between the physical data and existing planning/seabed information. This next step of our work involves characterising seabed in each planning zone type based on its sedimentology and geomorphology.

The Marine Park contains seven different planning zone types that occur below the low water mark (excluding 'Island' zones) (Fig. 5.1). Each individual planning zone type occupies a different proportion of the MP and has a colour and acronym code (Fig 3.3, Appendix F). In this chapter, we provide a brief overview of the main physical characteristics (i.e. texture, composition and geomorphology) of the seabed in each of the seven planning zone types (Appendices G and H) and also predict the habitats that may be associated with each zone type. A more detailed description of the sedimentary and geomorphic features of the planning zones is provided in Appendix I. The spatial distribution of the physical features in each of the planning zones is shown in a series of maps (Appendix J).

5.1. PHYSICAL CHARACTER OF THE PLANNING ZONES

The seabed in each of the different planning zone types contains a set of physical characteristics (Tables 5.1 and 5.2) that reflect their location within the MP, such as water depth and proximity to rivers. Some of the trends outlined in chapter 4 are represented in the planning zones. Such physical characteristics provide insights into the nature of seabed habitats and may also enable the later prediction of habitat boundaries.

5.1.1. Scientific Research Zone (SRZ)

SRZ's are situated around islands and reefs, and in seabed areas that are generally dominated by coral edifices, such as around Lizard Island and the Capricorn Group (Fig. 1.1). Reefs and bank/shoals make up the largest percentage of the seabed in SRZ compared to other planning zones (Fig. 5.2, Appendix I and J). The abundance of reefs is reflected in the dominant sediment components. As reef edifices influence seabed sediments up to 2 km away (Flood et al., 1978), high carbonate (bulk, sand and mud) concentrations (>65%) in these zones (Table 5.2) reflects a local carbonate sediment source. Concentrations of >60% sand (96%) and >60% carbonate sand (88%) characterise the seabed, and although it is similar to concentrations in General Use Zones (GUZ) and Preservation Zones (PZ), they cover the largest area of all the planning zones (Appendix H). Carbonate sand grains may comprise coral and skeletal detritus, such as foraminifera, molluscs and coralline algae (Flood et al., 1978) and *Halimeda* from banks on the outer shelf (Orme and Salama, 1988). SRZ have low mean mud contents (9%)

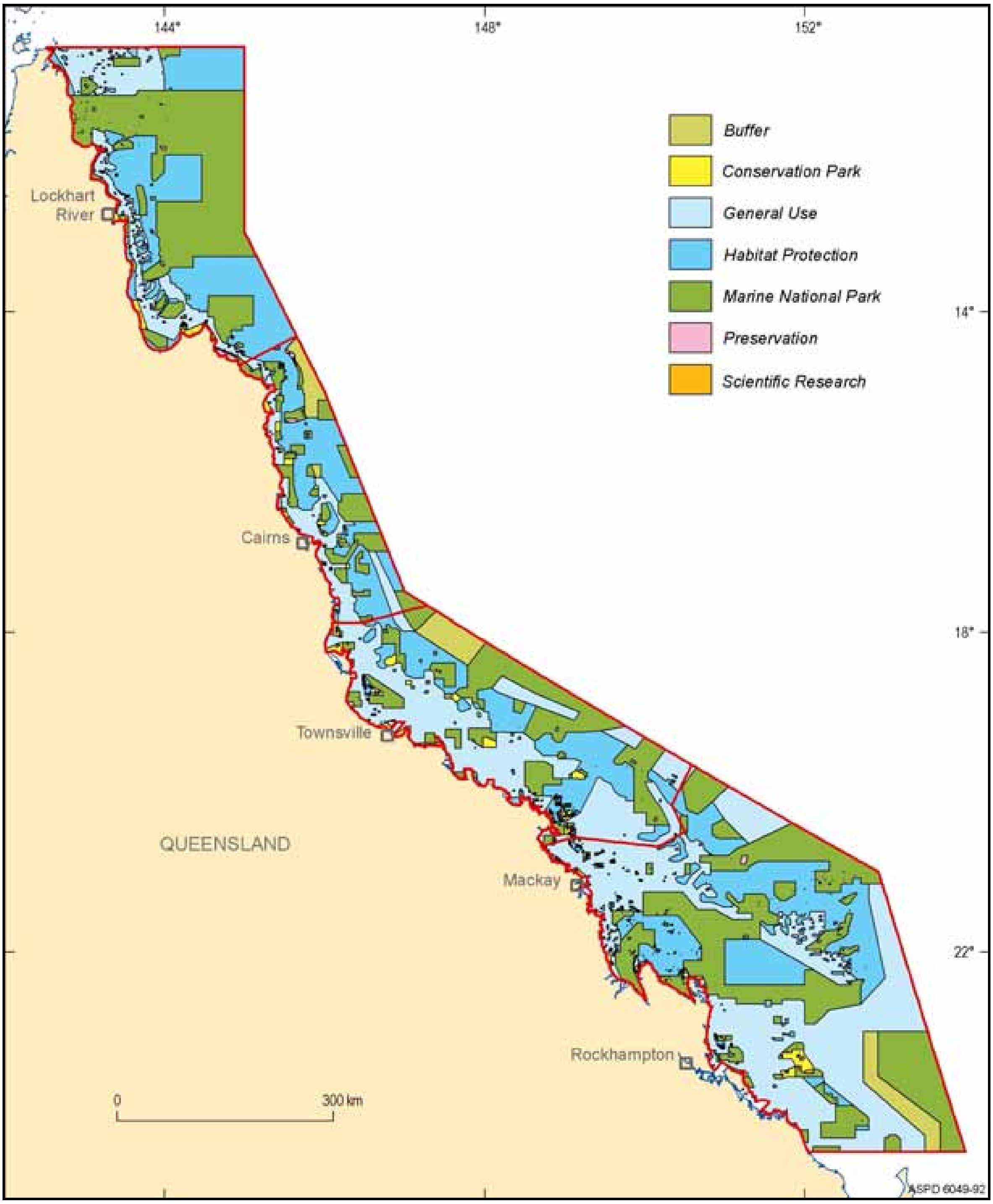

Figure 5.1. Map of the planning zones and their distribution within the Marine Park (with permission from GBRMPA). Complete maps of the planning zone boundaries can be found at: www.gbrmpa.gov.au/corp_site/management/zoning/zoning_maps.html.

which is the lowest compared to the other zones (Table 5.1). Low mud contents may reflect the great distance of these zones from river outflows and the removal of fine sediment components caused by the local acceleration of tidal currents in inter-reefal channels between reefs (Maiklem, 1966).

5.1.2. Preservation zone (PZ)

The seabed in PZ's is dominated by shelf (43%) and reef features (31%) (Fig. 5.2, Appendix I). The majority of PZ occur on the middle and outer shelves, locally associated with seabed areas with high reef density (Appendix J). High mean sand concentrations (64%), and high mean bulk carbonate (67%) and carbonate sand (78%) contents reflect skeletal carbonate grains nearby to reefs in inter-reefal areas of the shelf. Sediments on the middle and outer shelves have similar concentrations of these sediment attributes (Appendix D). The percentage area covered by >60% bulk carbonate is similar to the coverage in Marine National Park Zones (MNPZ's) (Appendix I). The other major geomorphic features of reefs, plateaus and bank/shoals would generate high carbonate. Reefs cover the second highest percentage area compared to the other zones, which would influence carbonate sediment supply (Flood et al., 1978).

Seabed habitats in PZ and SRZ are influenced by strong tidal currents in inter-reef passages and on reef margins (Hopley, 1982). By dispersing sediments, tidal currents produce seabed disturbance, and localised inter-reefal upwelling influences nutrient pathways into the lagoon (Alongi, 1997). In general, these two zones contain a mixture of potential habitats including: 1) unconsolidated sandy substrates and soft sediment habitats; and 2) hard coral surfaces and rocky substrates for attaching biota (Post et al., 2006).

Table 5.1. Sediment grain size statistics for each planning zone.

Zone	Statistics	%Gravel	%Sand	%Mud
Scientific Research	*Min:*	2	30	0
	Max:	65	96	41
	Mean:	11	79	9
	Std Dev:	8	13	10
Preservation	*Min:*	1	7	0
	Max:	89	98	75
	Mean:	13	64	22
	Std Dev:	13	18	21
Conservation Park	*Min:*	0	6	0
	Max:	60	99	90
	Mean:	10	60	30
	Std Dev:	9	21	23
Buffer	*Min:*	0	2	0
	Max:	97	97	90
	Mean:	21	46	32
	Std Dev:	37	30	28
Habitat Protection	*Min:*	0	2	0
	Max:	97	99	98
	Mean:	16	62	22
	Std Dev:	17	20	21
Marine National Park	*Min:*	0	0	0
	Max:	97	100	100
	Mean:	14	60	25
	Std Dev:	18	24	25
General Use	*Min:*	0	4	0
	Max:	90	100	95
	Mean:	8	67	25
	Std Dev:	8	20	21

5.1.3. Conservation Park Zone (CRZ)

CRZ's contain the most extensive percentage area of shelf (72%), compared to the other planning zones (Fig. 5.2, Appendix I and J). A large proportion of CRZ's occur on parts of the inner shelf and in close proximity to rivers, which is reflected by the high mean mud content (30%) of sediments (Table 5.1). The percentage area of >80% mud is comparable to concentrations in MNPZ's (Appendix I). Many of these zones are located along parts of the terrigenous sediment wedge (e.g. Belperio, 1983a). Sediments are terrigenous in composition, with the lowest mean bulk carbonate, carbonate sand and carbonate mud concentrations (46%, 55%, and 32%, respectively) overall (Table 5.2). Riverine sediments are trapped in the nearshore zone where they become suspended by waves and tides, producing waters with high turbidity (Alongi and McKinnon, 2005). Although the other major geomorphic features in this zone include reefs and bank/shoals, carbonate sediments could be overwhelmed by terrigenous grains.

In CRZ's, the seabed is subject to physical disturbances from waves and by changing rates of fluvial sediment supply (Alongi, 1997). Habitats in this environment are dynamic and would need to constantly adapt to disturbances and modification by sediment inputs (i.e. mud drape). Such muddy habitats probably have a less abundant community of fauna than sandy or hard substrates (e.g. Pitcher et al., 1997). CRZ's in Lloyd and Bathurst Bays

Table 5.2. Sediment composition statistics for each planning zone.

Region	Statistics	%Bulk Carbonate	%Carbonate Sand	%Carbonate Mud
Scientific Research	*Min:*	12	11	8
	Max:	93	93	84
	Mean:	78	79	67
	Std Dev:	21	21	23
Preservation	*Min:*	15	11	0
	Max:	99	97	94
	Mean:	67	78	48
	Std Dev:	25	15	26
Conservation Park	*Min:*	1	2	0
	Max:	97	95	89
	Mean:	46	55	32
	Std Dev:	28	29	25
Buffer	*Min:*	28	25	26
	Max:	95	94	91
	Mean:	70	88	72
	Std Dev:	14	10	17
Habitat Protection	*Min:*	0	2	0
	Max:	99	100	95
	Mean:	76	81	65
	Std Dev:	19	18	25
Marine National Park	*Min:*	0	1	0
	Max:	100	98	95
	Mean:	67	70	57
	Std Dev:	24	26	25
General Use	*Min:*	0	1	0
	Max:	99	100	95
	Mean:	59	61	54
	Std Dev:	26	61	26

contain fringing reefs, and such environments would be subject to terrigenous mud inputs.

5.1.4. Buffer Zone (BZ)

BZ contain the most extensive areas of slope (59%), and generally contain deep water seabed environments, with only minor proportions occurring on the shelf (2%), such as offshore Cooktown (Fig. 1.1, Fig 5.2, Appendix I and J). The predominance of slope geomorphic features is reflected in the dominant sediment components. BZ's contain the highest mean mud concentrations (32%) and the lowest mean sand concentrations (46%) (Table 5.1). This reflects an increase in fine-grained components compared to the other zones, as mud particles are transported off the shelf and to distal slope regions. BZ's contain the highest mean gravel (21%) concentrations of any zone, which may reflect an increase in coarse grained sediment components associated with exposed hard substrates on the slope, such as rocky and escarpments submerged reefs (Harris et al., 2005). Geomorphic features such as trench/troughs and canyons are the most abundant in BZ's compared to the other planning zones (Appendix I). They separate the shelf from the offshore plateaus, forming conduits for shelf sediments into deeper waters (Harris et al., 2005). The highest overall mean carbonate sand (88%) and carbonate mud (72%) concentrations in BZ's (Table 5.2) indicate that a large volume of all sediment components are derived from high carbonate sediment producing regions the middle and outer shelf.

The seabed habitats of this zone may be controlled by water depth, sediment flux and sediment failure, as shelf sediments are redistributed off the continental shelf and transported into deeper waters via troughs and canyons (e.g. Davies et al., 1991). Environments where large volume sediment deposition takes place may be prone to slumping, and hence would produce unstable seabed habitats (Canals et al., 2004). Away from zones of active sediment movement, exposed rocky substrates and reefs may provide a sheltered refuge for attaching fauna.

5.1.5. General Use Zone (GUZ)

A large proportion of GUZ's are dominated by shelf (55%), which covers the second highest area out of all planning zones (Fig 5.2, Appendix I and J). This zone contains a range of geomorphic features, which in addition to shelf, also include: slope, plateaus, basins, terraces and saddles. Together these features broadly indicate that a range of seabed environments occur in GUZ. GUZ's have the second highest mean sand content (67%) compared to the other planning zones (Table 5.1). Sand concentrations of >60% cover 60% of the total area of GUZ's (Appendix G). Sandy sediments (>60%) cover extensive inter-reefal areas in the MP (43%) (Appendix E). Mean mud concentrations (25%) are the same as those in MNPZ's and correspond to the outer edge of the terrigenous sediment wedge and parts of the shelf edge and upper slope (Appendix J). Reefs only cover a minor proportion of GUZ's (1%) which is the lowest coverage of any shelf-dominated zone (Appendix I). Low mean gravel concentrations (8%) may reflect the high number of shelf features in GUZ (i.e. Chapter 4), as generally shelf areas contain low gravel concentrations (Figs. 4.3-4.5) and lack coarse coral gravel fragments associated with talus slopes (e.g. Hughes, 1999). Compared to Habitat Protection Zones (HPZ's), which contain abundant reefs, the low mean bulk carbonate concentrations (59%) in GUZ's reflect this lack of reefs and location on parts of the inner shelf, which is largely influenced by terrigenous sediments (Table 5.2). Similarly, carbonate sand concentrations are lower than HPZ's and MNPZ's, even though percent sand contents are comparatively higher, which suggests that the composition of sand-sized sediments in GUZ's, are mixed carbonate-siliciclastic (Appendix G). Large proportions of GUZ's are situated away from the influence of terrigenous sediments, which suggests a relict sediment component (e.g. Maxwell, 1968b). Relict sand grains may be derived from two main sources: depocentres around continental islands on the middle shelf (Heap et al., 2002), and on southern parts of the outer shelf (Marshall, 1977). Both these locations occur in the vicinity of GUZ's.

The largely inter-reefal areas occurring in GUZ's suggests a prevalence of large expanses of soft sandy substrates comprised of terrigenous, carbonate, and mixed terrigenous-carbonate sediments. Other habitats comprise nearshore terrigenous mud and silt, interspersed with rock outcrops and areas of exposed bedrock, deep reefs and shoals (Pitcher et al., 1997). Extensive inter-reefal areas in the central GBR lagoon (e.g. offshore Hinchinbrook Island) undergo low and variable sedimentation rates and episodic physical reworking (Alongi, 1989). Such sandy environments contain abundant biota, dominated by infauna such as polychaetes and amphipods, but lack bivalves (Alongi, 1989; Pitcher et al., 1997).

5.1.6. Habitat Protection (HPZ) and Marine National Park Zones (MNPZ)

The seabed geomorphology and sediments of HPZ's and MNPZ's share similar characteristics (Tables 5.1 and 5.2, Fig 5.2, Appendices G, H, I and J). These zones are mostly situated on the middle and outer shelves and the continental slope (Figs. 1.1 and 5.1). The shelf is the most extensive in each zone and covers >30% of each (Appendix I). Mean sand concentrations in HPZ's (62%) and MNPZ's (60%) are comparable (Table 5.1), showing that the seabed in these two zones share similar sediment textures. Concentrations of >60% sand cover 40% and 30% of HPZ's and MNPZ's, respectively (Appendix G). This difference may be explained in terms of higher numbers of reefs and adjacent inter-reefal areas in HPZ's compared to MNPZ's (Appendix I). HPZ's and MNPZ's contain similar mean mud contents of 22% and 25%, (Table 5.1) respectively. This reflects the relatively large percentage of these zones that occur on the slope, which is the second most abundant feature in both HPZ's and MNPZ's (24%, 29%) (Appendix I). The mean gravel content of HPZ's and MNPZ's attain 16% and 14% respectively, and are the second highest after BZ's (Table 5.1).

High mean bulk carbonate contents of 76% in HPZ's and 67% in MNPZ's are comparable to bulk carbonate on the outer shelf and continental slope (Table 5.2), and reflect the supply of carbonate grains from areas of high reef density (Orme and Flood, 1980). Reefs and plateaus form large parts of these two zones (Table 5.2), and inter-reefal areas adjacent to reefs, such as parts of Swain Reefs, which is bordered by several HPZ's (Figs. 1.1, 5.1), would provide a regular supply of skeletal carbonate sediment. Sediments in HPZ's contain higher overall carbonate contents than MNPZ's (Table 5.2), which may reflect the occurrence of larger proportions of HPZ's on the outer shelf, and surrounding reefs. In general, the location of some HPZ's and MNPZ's nearby continental islands such as Palm Island and Whitsunday Islands, which supply quartz and other mineral grains to the shelf, may replace carbonate sediments with siliciclastic components (Appendix J). Relict grains may influence the composition and amount of terrigenous versus carbonate components where these zones occur in Broad Sound (Cook and Mayo, 1977) and Capricorn Channel (Marshall, 1977). Overall the distribution of carbonate sediments in these two zones, would exhibit across-shelf variation and longitudinal (along-shelf) gradients due to the abundance and occurrence of carbonate-producing biota in inter-reefal areas (Marshall and Davies, 1978).

The seabed habitats in these zones would largely be determined by the ratio of reefal to non-reefal environments. Coarse gravely sediments would predominantly be associated with reefs, reef talus slopes, *Halimeda* meadows and relict deposits. Seabed habitats would consist of inter-reefal or shelf, talus slopes, reef margin (windward) and reef platform (e.g. Post et al., 2006). Reef macrofauna in the Gulf of Carpentaria was shown to have the highest benthic diversity compared to muddy (shallow) and deep water (basin) environments (Post et al, 2006). Such a relationship may also be a feature of habitats in HPZ's and MNPZ's.

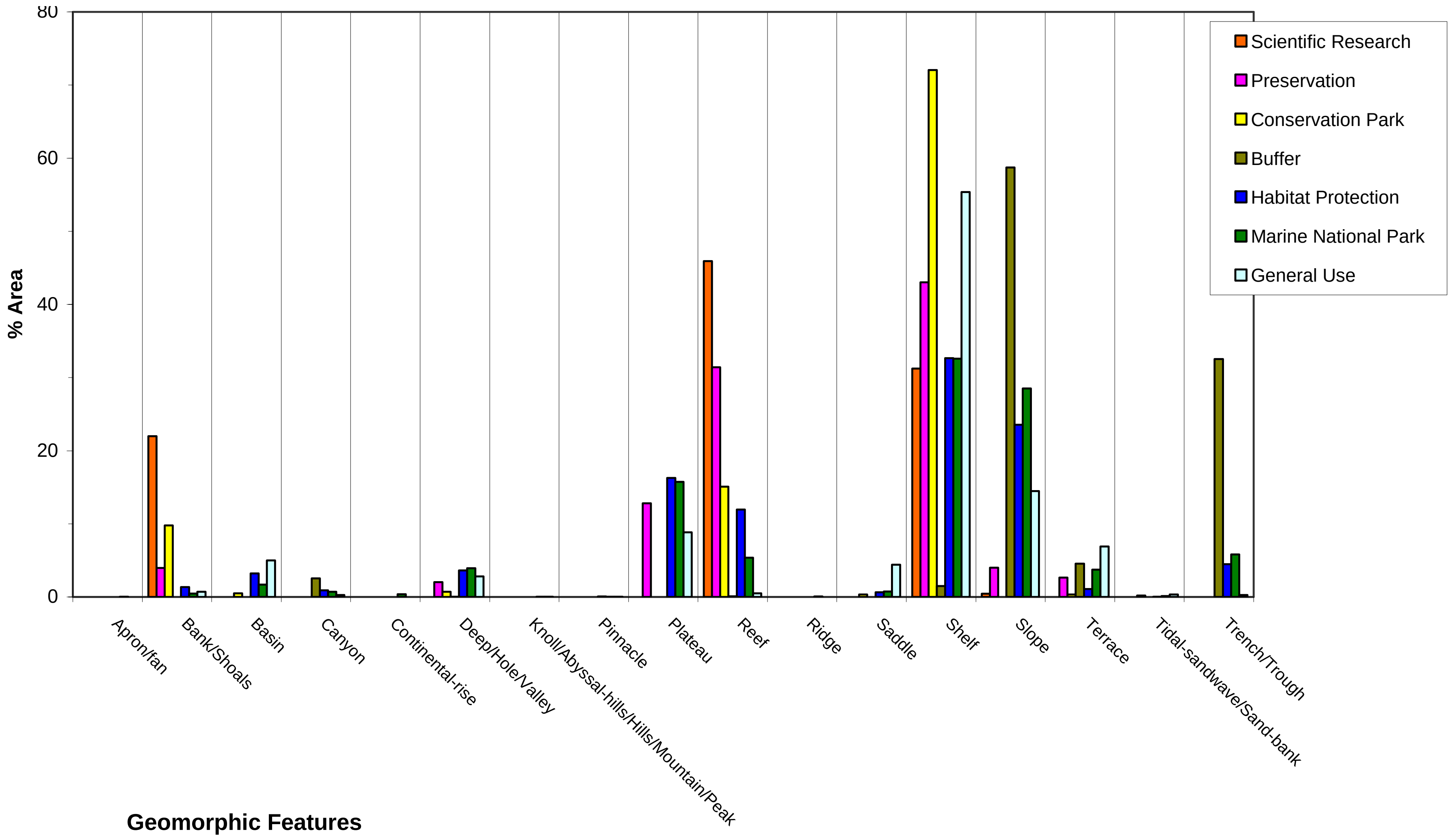

Figure 5.2. Comparison of geomorphic features between the planning zone types.

6. Discussion

The new data synthesised in this report broadens our understanding of the regional sedimentology in inter-reefal areas of the GBR Marine Park and also provides insights into the physical characteristics of the substrate in planning zones. We discuss below a new, more detailed representation of the regional sedimentology in terms of spatial distribution patterns, and source and supply, and make comparisons between our assessment and preceding facies models (cf., Maxwell, 1968; Belperio, 1983a). In addition we discuss the physical characteristics (e.g. sediments and geomorphology) of the substrate within each of the planning zone types, and identify some of the applications that our physical data has to marine park management, including the definition of seabed habitats.

This synthesis updates existing knowledge of the regional distribution and characteristics of seabed sediments from the shallow shelf to upper slope in the GBR Marine Park, in unprecedented detail. Overall, we present the most up-to-date representation of the regional surface sediment distributions for the tropical siliciclastic-carbonate GBR margin.

6.1. REGIONAL SEDIMENT FACIES

6.1.1 Occurrence and distribution

Most of the inter-reefal areas are gravel poor, however, significant gravel concentrations occur locally, associated with individual reefs. This pattern suggests that gravel-sized sediments are derived from nearby reef edifices, which corroborates our observations that the sand and gravel fractions are principally composed of carbonate grains. Also, high gravel concentrations between the reefs form a coarse lag, produced from winnowing of finer grains by locally accelerated tidal currents in the narrow passages between the reefs. Similarly, the local occurrence of gravel-rich sediments in Broad Sound on the inner shelf is a result of the strong tidal currents in the embayment (Cook and Mayo, 1978).

Sand displays the greatest variability of all the size fractions, with the distributions and abundances generally inversely related to mud concentrations. Compared to the mud and gravel concentrations, the sand concentrations are highly variable on the outer shelf, amongst the reefs, with concentrations of >40% common adjacent to reefs. This highly variable and heterogeneous distribution is consistent with some of the carbonate sand fraction being sourced from the reefs and undergoing minimal dispersal, in addition to the sand derived from skeletal foraminifer, mollusc and in-situ *Halimeda*. Generally, sand concentrations are relatively low on the inner and middle shelves of the central and northern GBR, except in the far north where concentrations generally increase across the shelf, and in the far south where the largest contiguous area of sandy sediment occurs south of Broad Sound. Here, concentrations of >80% cover ~22,000 km^2 and extend across the shelf. Such high concentrations could be explained by several mechanisms including, input of relict grains from shelf depocentres (e.g. Heap et al., 2002), northward transport of silica sands from Fraser Island and Hervey Bay (e.g. Boyd et al., 2004), or the sporadic supply of fluvial sand from the Fitzroy River (e.g. Ryan et al., 2007). In general, offshore increases in sand concentrations correspond to an increase in bulk carbonate concentrations (see below).

Generally, mud concentrations are relatively uniform across the GBR with most variability occurring north of 18° S, although concentrations are generally lowest on the outer shelf. The largest contiguous regions of low (<20%) mud concentrations occur on the outer shelf south of 18° S and on the inner shelf south of 21° S. North of these latitudes, high mud concentrations occur on the inner shelf (especially in north-facing embayments) and in between the reefs where the shelf is narrowest, between 18° S and 15° S. The distribution and abundance of terrigenous mud does not show any significant correlation with carbonate mud (see below). This indicates that the patterns in the mud fraction reveal a strong terrigenous influence. Areas of high mud and low carbonate mud occur in the Capricorn Channel, Princess Charlotte Bay, and numerous north-facing embayments. The heterogeneity displayed by the mud fraction on the inner shelf is restricted to the scale of individual embayments. Variable concentrations on the inner-shelf indicate the restricted influence of coastal rivers in delivering sediment to the inner shelf. Terrigenous mud is principally concentrated at river mouths where it forms muddy deltas (e.g., Burdekin River mouth; Belperio, 1983a). Interestingly, a distinct NW-trending region of relatively high mud concentrations (>40%) occurs on the middle shelf south of 19° S, and separates two contiguous regions of low (<20%) mud concentrations on the inner and outer shelf. Although we have no direct evidence of the age of the sediment on the shelf, this region of relatively high mud concentrations is probably a relict feature where mud was deposited on the middle shelf possibly by rivers crossing the shelf at lowstand (e.g. Marshall, 1977).

Carbonate concentrations vary across the shelf with water depth and with distance from the coast, resulting in a distinct shelf-parallel zonation (Appendix A). Sediments on each part of the continental shelf (i.e. inner, middle and outer shelf) contain distinct carbonate contents, whereby low (<40%) carbonate concentrations occur on the inner shelf, moderate concentrations (40-60%) occur on the middle shelf and high (>60%) carbonate concentrations on the outer shelf and regions of high reef density. This distribution pattern is most pronounced in the bulk carbonate and carbonate mud fractions, and less distinct in the carbonate sand fraction, which is highly variable and corresponds with the variability shown in the sand fraction.

On the outer shelf, the highest bulk carbonate concentrations occur adjacent to the outer shelf reefs. The largest contiguous area (~65,000 km^2) of >80% bulk carbonate occurs on the outer shelf south of 18° S, where an abundance of reefs occur. Elevated carbonate concentrations (>40%) only occur next to the coast in a few places, including Broad Sound, Curtis Island, Whitsunday Islands, and northern Princes Charlotte Bay. These areas are associated with relatively low river input. Other local-scale variations in the across-shelf carbonate zonation are evident in the data. For example, offshore Rockhampton the seabed contains variable carbonate concentrations, where locally, areas with relatively high carbonate concentrations are interspersed with broader regions of lower carbonate concentrations. Similar patterns are also evident next to islands where relatively high carbonate concentrations occur in the narrow passages between the islands, compared with much lower concentrations on the surrounding shelf (Heap et al., 2002). Such distribution patterns may be caused by redistribution of sediments by tides and/or the presence of relict deposits (Maxwell and Swinchatt, 1970).

Textural and compositional characteristics of the slope sediments display a significantly different regional character compared to the shelf sediments. Our data reveal that the sediments are almost entirely composed of carbonate grains with concentrations of >60% for all samples collected on the slope. Variability in the fractions is low compared to the shelf sediments. Beyond the GBR marine park boundary, Dunbar and Dickens (2003) show there is an overall decrease in carbonate concentrations away from the shelf edge.

Overall, the spatial distribution patterns of surface sediments at local and regional scales indicate broad shelf trends and much more localised heterogeneity on inter-reefal parts of the GBR seabed than has been previously captured in the sediment models (cf., Maxwell, 1968; Belperio, 1983a). Much of the regional and local-scale variability has been reported in case studies (e.g., Belperio, 1983a; Carter et al., 1993; Flood et al., 1978; Heap et al., 2002; Lambeck and Woolfe, 2000; Larcombe and Carter, 2004; Orpin et al., 1999; Scoffin and Tudhope, 1985; Woolfe et al., 2000). However, none of these previous studies have put their results into a regional context or undertaken a quantitative spatial analysis. Our study is the first to combine these data into a consistent, robust regional quantitative spatial dataset. Generally, sediments in inter-reefal areas exhibit a high degree of textural and compositional heterogeneity that has been missing from existing sediment models for the GBR shelf. Our data reveal that the seabed sediments of the inter-reefal areas of the GBR marine park form a complex mosaic that reflects the mixing of two main sediment types and results in considerable benthic diversity.

6.1.2. Sediment sources and supply

Sediment distribution patterns on the GBR shelf reflect two primary sediment sources, which have a modern and relict origin. Terrigenous grains are derived from fluvial inputs and remobilised relict deposits, and carbonate grains are supplied principally from *in-situ* production of skeletal carbonate with smaller inputs from relict sources (e.g., Maxwell, 1968; 1973; Belperio, 1983a; Devlin and Brodie, 2005; Heap et al., 2002; Orpin et al., 2004; Orme et al., 1978b; Scoffin and Tudhope, 1985).

On the GBR shelf, only very small amounts of terrigenous gravel are generally transported to the shelf by local rivers. This is because very little gravel is contained in the catchments and most of this is deposited in coastal and estuarine environments (Nakayama et al., 2002). The export of terrigenous sand to the shelf also varies considerably along the coast (Neil et al., 2002), with most sand being transported to the coast by rare, large magnitude flood events (Bryce et al., 1998). As such, fluvial sands comprise a low percentage of shelf sand, and their distribution is patchy and restricted to the inner shelf, adjacent to river mouths.

Despite this, extensive areas of siliciclastic sand occur in the far north and south of the GBR marine park (Appendix A). In the south, these sands may be derived from the Hervey Bay/Fraser Island region. Although this region lies at the interface between the longshore sediment transport system and the southward-flowing East Australia Current, intermittently sand may be transported northward into the marine park by currents generated by the SE trade winds (e.g., Woolfe et al., 2000; Boyd et al., 2004). North of Cooktown, silica sand from coastal dunes and catchments is delivered to the coast by local rivers, where the sand is dispersed along the shallow inner-shelf by wind-driven currents (Lambeck and Woolfe, 2000). Unlike the catchments to the south, these small coastal catchments in the north contain little mud and most of the sediment delivered to the coast is sand. Siliciclastic sands are also derived from granite headlands, islands (Orme et al., 1978b), and relict bedforms on the seabed (e.g., Marshall 1977). However, over most of the

GBR region, terrigenous sediments are aggraded into coastal dunes, beach ridges and strandplains (e.g., Woolfe et al., 1998; Belperio, 1983a).

The terrigenous sediment fraction on the shelf is primarily comprised of mud, which is because mud comprises most of the sediment delivered to the coast by rivers (Orpin et al., 2004), and significant amounts of relict mud have been reworked from the shelf during the latest post-glacial transgression (Carter and Johnson, 1986; Carter et al., 1993; Heap et al., 2002; Larcombe et al., 1995b; Larcombe and Carter, 1998). Presently, this mud is a significant constituent of the inner-shelf terrigenous sediment wedge (Belperio, 1983a). The inner-shelf sediment wedge is mostly made up of modern Holocene sediments including clay, silt and very fine to coarse sand grains (Woolfe et al., 2000). Concentrations of mud in this sediment wedge are variable (Appendix A) and reflect local variations in the supply and dominant sediment type from the catchments (i.e. Maxwell, 1968a). Changes in predominant catchment rock types (i.e. volcanic, granitic, sedimentary, metamorphic) influence the composition of fluvial siliciclastic grains on the shelf, with variations occurring along the coast associated with catchment geology (e.g. Burdekin, Fitzroy) (Maxwell, 1968a; Lambeck and Woolfe, 2000).

Generally, strong landward partitioning of terrigenous sediment along the GBR results in little modern siliciclastic material reaching the middle and outer shelves (Woolfe et al., 1998). Our data reveal an extensive area of mud on the middle shelf south of 19° S. Repeated large river flood plumes are one mechanism for distributing mud to the middle and outer shelves (Devlin and Brodie, 2005; McKergow et al., 2005). However, while visually impressive, the concentrations of mud in the plumes is generally quite low (Larcombe and Woolfe, 1999a; 1999b). More likely, is that significant concentrations of mud on the middle and outer shelf represent relict deposits that have been left stranded after the latest post-glacial marine transgression. The extensive mud deposits on the southern GBR middle shelf are interpreted to be supratidal mangrove and tidal flat sediments deposited during sea level lowstand (Marshall, 1977).

Relict terrigenous grains are important constituents of seabed sediments on the GBR shelf (Maxwell, 1968b; Maxwell and Swinchatt, 1970; Marshall, 1977). As modern terrigenous gravel is largely deposited in estuaries, regions containing high concentrations of terrigenous gravel on the middle shelf must be largely relict (Belperio, 1983a). These relict deposits generally comprise terrigenous rock fragments which form gravel lags produced by strong wave and tide currents (Marshall, 1977). Concentrations of relict sand have been identified in the southern GBR as moribund sandwaves (Marshall, 1977), and scouring on the windward reef margins has exposed relict terrigenous quartz (Scoffin and Tudhope, 1985). Simple flux-based models have shown that the quantity of mud deposited in inner shelf embayments and middle shelf depocentres (e.g., Carter et al, 1993; Heap et al., 2002) is up to an order of magnitude higher than that delivered by local rivers since the onset of the present highstand. This implies that significant quantities of relict terrigenous mud have been reworked and deposited in these depocentres during the latest post-glacial marine transgression to form the present seabed sediments.

The skeletal remains of carbonate organisms—mostly molluscs, foraminifers, *Halimeda* and coral—is by far the dominant fraction of the inter-reefal sediments on the GBR middle and outer shelf (Brunskill et al., 2002). However, these carbonate sediments are composed of modern and relict grains (Marshall and Davies, 1978). The concentration of each constituent varies across the shelf, in relation to water depth, nutrient availability, temperature, salinity, turbidity and substrate type (Lees, 1975). On a regional scale spatial patterns in carbonate concentrations reflect dilution by terrigenous grains.

Carbonate gravel concentrations are highest next to reefs on the outer shelf (Appendix A). Sediments in these regions comprise molluscs, foraminifers and coral fragments (Maxwell, 1968b; Hughes, 1999). Accumulations of gravel around reefs on the outer shelf also comprise relict carbonate gravel clasts, eroded from dead reef surfaces (Maxwell, 1968). These regions of high gravel concentration could provide potential sites for new coral reef growth. For example, the Holocene reefs grew on an existing substrate of gravelly sediments (Smithers et al., 2006). *Halimeda* debris in these regions is comprised of granule- and pebble-sized clasts, which suggests that many gravel-rich sites on the outer shelf may represent *Halimeda* meadows (Woolfe et al., 1998). On the inner-shelf where terrigenous sedimentation is higher, subaqueous dunes in Halifax Bay are composed of shelly gravelly sand (Larcombe and Carter, 2004).

High carbonate sand concentrations on the outer shelf reflect production of sand grains by wave action, which are significant around reefs (Flood and Orme, 1988). Foraminifera are the dominant constituent of sand-sized grains in the sediments of the inter-reef areas at these locations, followed by molluscs and coral fragments (Scoffin and Tudhope, 1985). Relict carbonate grains are also prominent. In Broad Sound, an area with high gravel concentrations in on the inner shelf, Cook and Mayo (1977) identified abundant relict gravel-sized calcareous nodules and coralline algae, which are dark-black in colour. In addition, relict *Halimeda* grains contribute strongly to the surface sediments on the middle and outer shelves of the northern GBR (Flood and Orme, 1988). In inter-reefal areas of the Capricorn Group, stained and encrusted foraminifera (*Marginopera*, *Alveolinella*) contribute to the abundance of relict grains found in these regions (Scoffin and Tudhope, 1985).

Lower gravel and sand concentrations on the slope indicate that the coarser fractions of modern sediments remain on the continental shelf and are generally not transported far from source. Much of the fine fraction comprises foraminiferal ooze formed by modern deposition of pelagic organisms, where fine soft sediments on the shelf edge and upper slope accumulate (Scoffin and Tudhope, 1985; Davies et al., 1991). Spatial variations in the carbonate concentrations reflect variable supply of carbonate from the outer shelf. In comparison, Harris et al. (1990) found that terrigenous mud dominated over pelagic carbonate north of the Burdekin River. Hence, the location and quantity of terrigenous grains being transported off the shelf may significantly influence the composition and distribution of sediment on the continental slope.

At a regional scale, our data reveal that carbonate-rich material dominates the seabed sediment in the inter-reefal areas of the GBR marine park. Sediments comprising >60% bulk carbonate cover 44.25% of the marine park and sediments containing greater than 80% bulk carbonate cover 25% of the park. This shows that carbonate sediments are a significant modern contributor to the bulk surface sediments. In comparison, terrigenous-dominated and relict sediments (bulk carbonate concentrations of <40%) cover 12.5% of the park and sediments containing <20% carbonate cover only 4.2% of the park. Areas of low carbonate concentrations near the coast demonstrate that local dilution of carbonate occurs, rather than a widespread restriction of calcareous supply. The development of sediment facies on the shelf is controlled primarily by the continuous production of carbonate grains in inter-reefal areas, and less so by terrigenous inputs, which have the most influence on the inner shelf.

6.1.3. Comparison with existing facies models of GBR shelf

While the general regional-scale trends in the texture and composition of surface sediments revealed by our data are consistent with the facies models generated by Belperio (1983a) and Maxwell (1968a), we find considerable detail that these models do not portray. The degree of spatial variation, particularly in the sand fraction, is significantly more complex that previously recognised by these models. Our data also indicate that the spatial variability in mud concentrations along the inner shelf is greater than proposed by the existing facies models. This variability is at the scale of individual embayments (100’s km^2), with relatively low concentrations at the mouths of rivers, and relatively high concentrations in the north-facing embayments. Furthermore, the concept that the inner-shelf terrigenous sediment wedge is comprised of mud does not hold according to our data. Mud concentrations are >20% but the distribution patterns show that mud forms local concentrations along the shelf, such as at river mouths, in north-facing embayments and the lee of headlands (Belperio, 1983a; Neil et al., 2002). Regionally, these concentrations are discontinuous along the inner shelf with sand grains replacing mud as the dominant fraction in the far north and south. Areas of sandy sediment form local patches in the central GBR region but form more contiguous regions in the north and south. This distribution may reflect northward transport and also the storage of sediments close to source (e.g., Lambeck and Woolfe, 2000).

Across-shelf increases in carbonate concentrations revealed by our data are locally consistent with the facies models of Maxwell (1968a) and Belperio (1983a). However, our data also reveal large areas of the inner- and middle-shelves that display significant spatial variation in carbonate concentration. These variations were only cursorily defined by previous workers, and their extensive distribution indicates that they are a prominent feature of the modern sediment facies distribution. Changes in the composition of surficial/modern sediments, to form patchy distributions, could reflect the occurrence of relict sediments in isolated shelf depocentres. On some parts of the shelf, little mixing occurs between relict and modern sediment grains (e.g. Maxwell, 1968b; Marshall, 1977). Such a distribution pattern would create abrupt changes in sediment facies, where modern sediments are deposited adjacent to areas of reduced/low modern sedimentation.

Despite our newly-generated quantitative dataset, there is still some uncertainty regarding the distribution of rocky outcrops on the seabed, due to the different equipment required to sample hard substrates, compared to the soft sediments sampled for this work. Local areas of rock outcrops and/or hard-grounds, such as Pleistocene limestone outcrops have previously been mapped on the middle shelf (>20 m) (Belperio, 1983a), towards the shelf edge east of Palm Passage (Scoffin and Tudhope, 1985), around the Whitsunday Islands (Heap et al., 2001), and in the scoured channel floors of inter-reefal channels (Harris et al., 2005). These areas have not been identified in our new sediment maps. Future seabed mapping work will reveal more of the regional distribution of rocky substrates on the shelf, which along with seabed sediments will present a more complete picture of seabed character.

6.2. SEABED ENVIRONMENTS AND HABITATS

Assessment of the physical nature of the seabed in the GBRMPA planning zones provides an improved understanding of the principal characteristics of the substrate and insights into the seabed habitats of each zone. The substrate of each planning zone is defined by its sedimentary and geomorphic characteristics, which are associated with different seabed environments. By quantifying the substrate attributes of each planning zone, we can better understand the relationship of the substrate with broader patterns of sediment distribution, oceanography and geomorphology in inter-reefal areas within the Marine Park. Together, the texture and composition of surface sediments, and the range of geomorphic features, provides fundamental baseline information that can be used to monitor potential changes to the seabed habitats.

6.2.1. Implications for Marine Park management

Given the large area of inter-reefal seabed (325,590 km^2) in the Great Barrier Reef Marine Park, a detailed understanding of the benthic biodiversity of the entire region from biological data, would be hampered by the high cost of data collection. Variation in the character and type of the physical substrate is one of the key influences on the distribution of biological communities, along with sediment dynamics and physical processes such as near-bed currents (Snelgrove and Butman, 1994; Beaman and Harris, in press). Our synthesis of seabed sediments and geomorphic features from new data provides a comprehensive physical dataset to aid in developing a more complete picture of the nature of seabed environments in the Marine Park and in planning zones, than has been previously achieved. Ultimately, this physical dataset may be used together with biological datasets to characterise the seabed.

Regional maps of the distribution of seabed habitats can be completed relatively rapidly by incorporating a range of biophysical datasets (e.g. Whiteway et al., 2007). The biophysical elements of the seabed, such as sediments, seabed water temperature and primary productivity, can be used collectively to represent a spatial 'seascape' layer. In particular, seascapes provide an alternative in situations where large parts of the seabed are devoid of samples (e.g. slope areas), and it is not practical to obtain extensive (regional) biological data in a short time frame (Whiteway et al., 2007). Together, the sedimentary and geomorphic characteristics of each of the planning zone types has implications for whether existing planning zone boundaries adequately capture and ultimately protect the variability and heterogeneity of the substrate and the seabed habitats. Our quantitative spatial datasets provides robust baseline physical information, which can be used as a management framework from which to monitor habitats and assess future planning initiatives in the Marine Park. This approach will result in improved outcomes for decision making and marine park management.

Our quantitative spatial analysis of the texture and composition of the seabed is a systematic means of understanding the distribution of potential habitats within the planning scheme. The main advantage of using sediment data is that patterns and substrate variations can be determined across broad regions, even in areas that lack biological data. As a surrogate for biological information, these data provide the best possible spatial information at a regional scale that allows managers to make robust quantitative comparisons between different habitat types in Australia's highest profile World Heritage Area.

This work has revealed that each zone contains a set of sedimentary and geomorphic characteristics (i.e. chapter 5). Overall, low (<20%) gravel contents dominate in the majority of zones, which is consistent with the occurrence of inter-reefal sediments away from reefs, on the shelf. Sand concentrations are high (>60%) overall, with just one zone containing relatively lower amounts of sand (i.e. Buffer zones), which is consistent with the significant decrease in sand that occurs in slope environments. Mud contents vary in the zones, depending on the predominant shelf and/or slope region captured by the zone type. Carbonate contents also vary between zone types, in relation to shelf/slope area. High terrigenous compositions are found in zones that cover the inner shelf, which is in contrast to high carbonate compositions on the middle and outer shelves. The shelf parallel distribution of sediments is reflected in the character of planning zones. Zones dominated by reefs contain high bulk carbonate contents, in addition to high carbonate sand and carbonate mud concentrations. Zones dominated by the inner shelf and continental slope contain low carbonate mud contents.

The inter-reefal seabed in planning zones is comprised of several sedimentary environment types (in addition to the reefs). The main types include; 1) sand- and carbonate-rich around islands and reefs on the middle and outer shelves, 2) gravel- and mud-rich with low carbonate in slope areas, 3) slightly muddy with low to moderate carbonate in inner shelf and slope regions, and 4) muddy, gravel- and carbonate-poor in river-influenced regions on the inner shelf. In particular, unconsolidated sediments that cover the shelf, slope, plateaus, trench/troughs and basins, are generally extensive in the planning zones. The fine-scale patchiness of sediments in some inter-reefal areas may reflect the variable and patchy distribution of distinctly different habitats. Although inter-reefal habitats may contain distinct patterns, unconsolidated sediment habitats may be more difficult to predict, as the boundaries between soft substrate habitats are not as sharply defined as the boundaries on hard substrates (Beaman and Harris, in press). The scale of such physical variations and the boundaries between contrasting compositional and/or grainsize patches may be better understood by our regional maps of the planning zones.

The definition of seabed habitats can be assisted by way of detailed assessment and comparison of the physical characteristics of significant areas. To further develop methods for habitat prediction, we need to develop our understanding of the relationships between biotic and abiotic components, using integrated science and comparable datasets. Further work, to investigate the links between sediments, habitats and marine biota in general, is necessary for the conservation and appropriate future management of inter-reefal areas.

7. References

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8. Appendices

8.1. Appendix A - Sediment grain size and composition maps

Regional figures showing the distribution of %gravel, %sand, %mud, %bulk carbonate, %carbonate sand and %carbonate mud in each of the four large management sections of the Marine Park. These images are also available on the data CD-ROM.

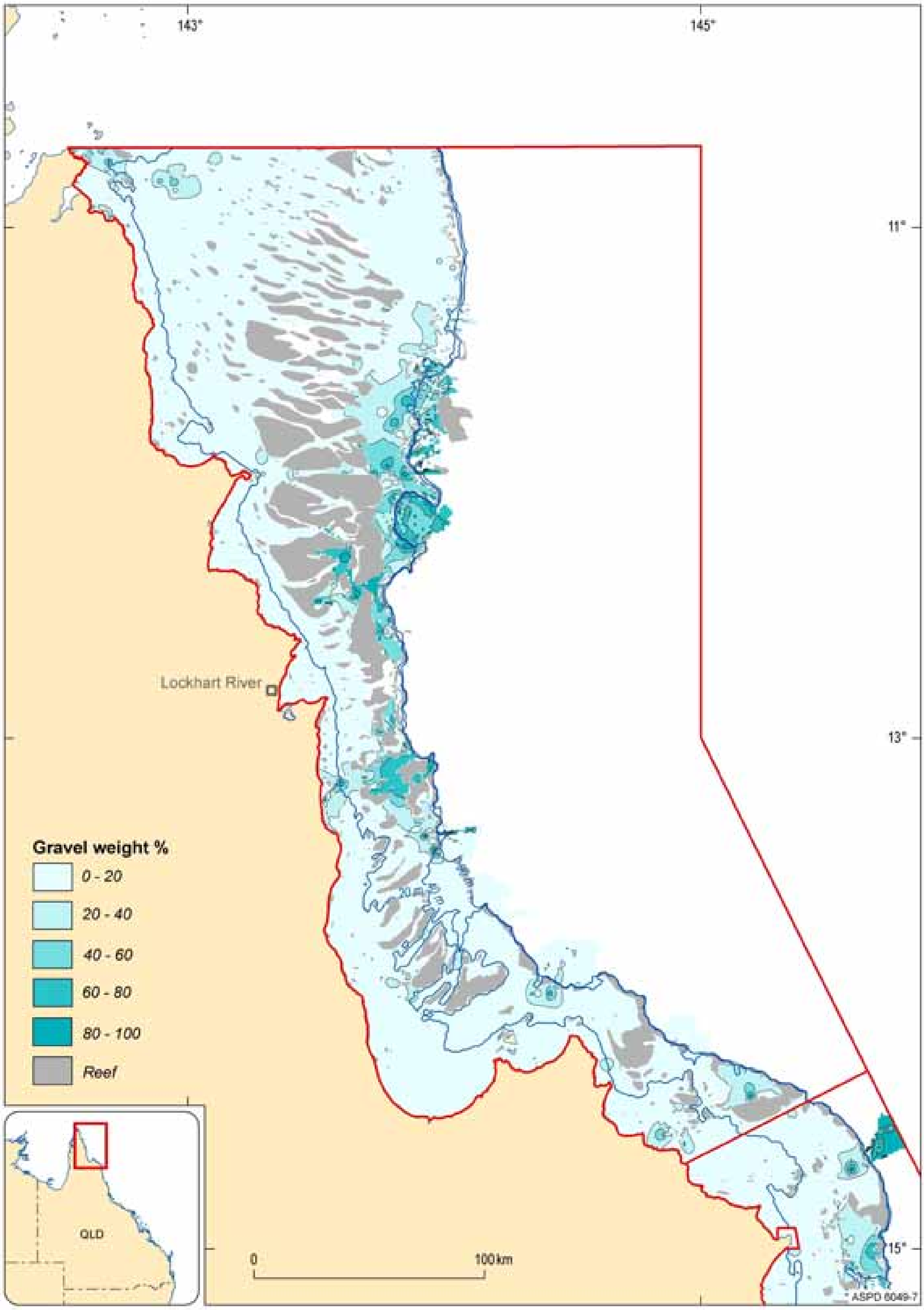

Figure 8.1. Percent gravel in the Far Northern Management Area.

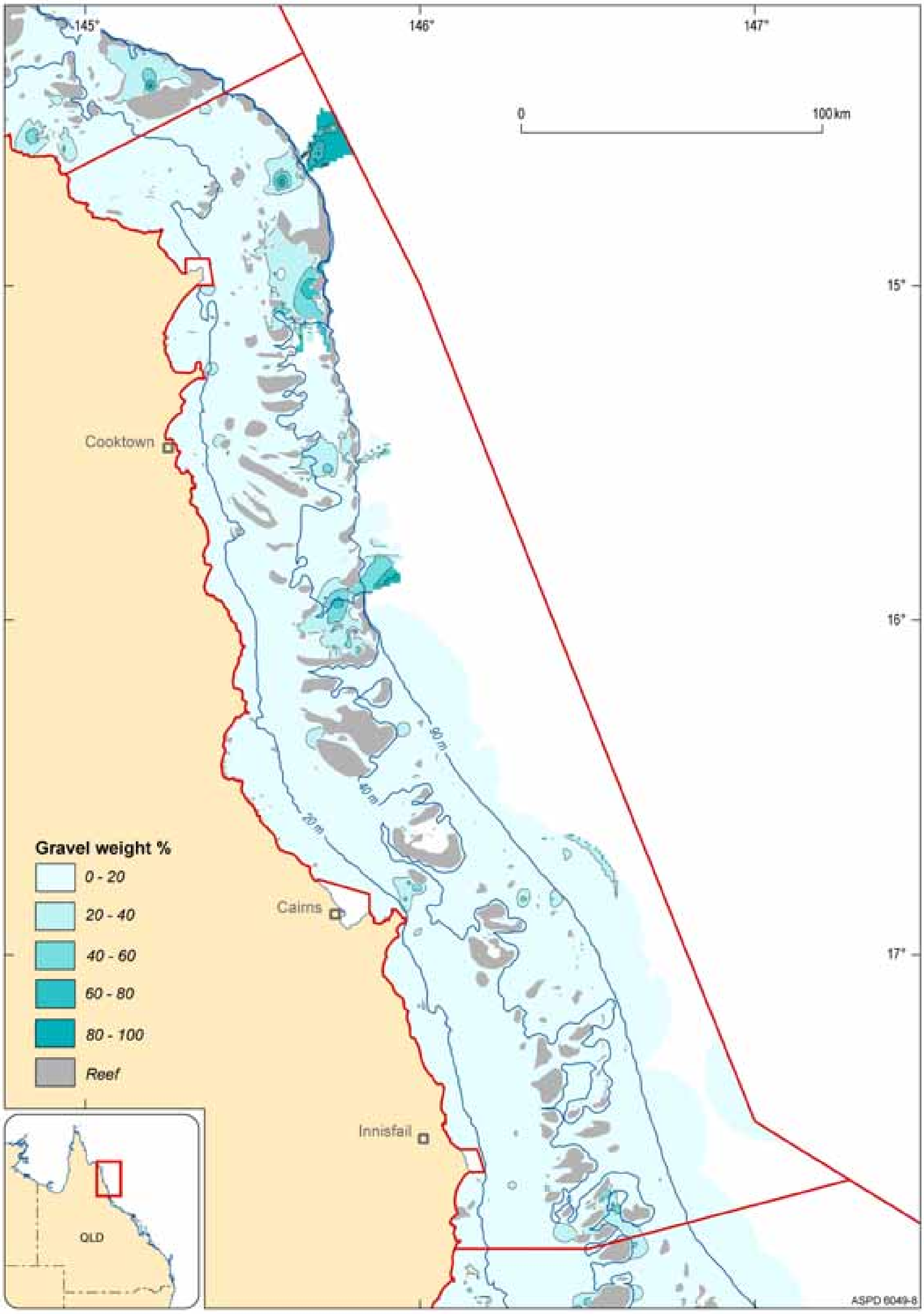

Figure 8.2. Percent gravel in the Cairns-Cooktown Management Area.

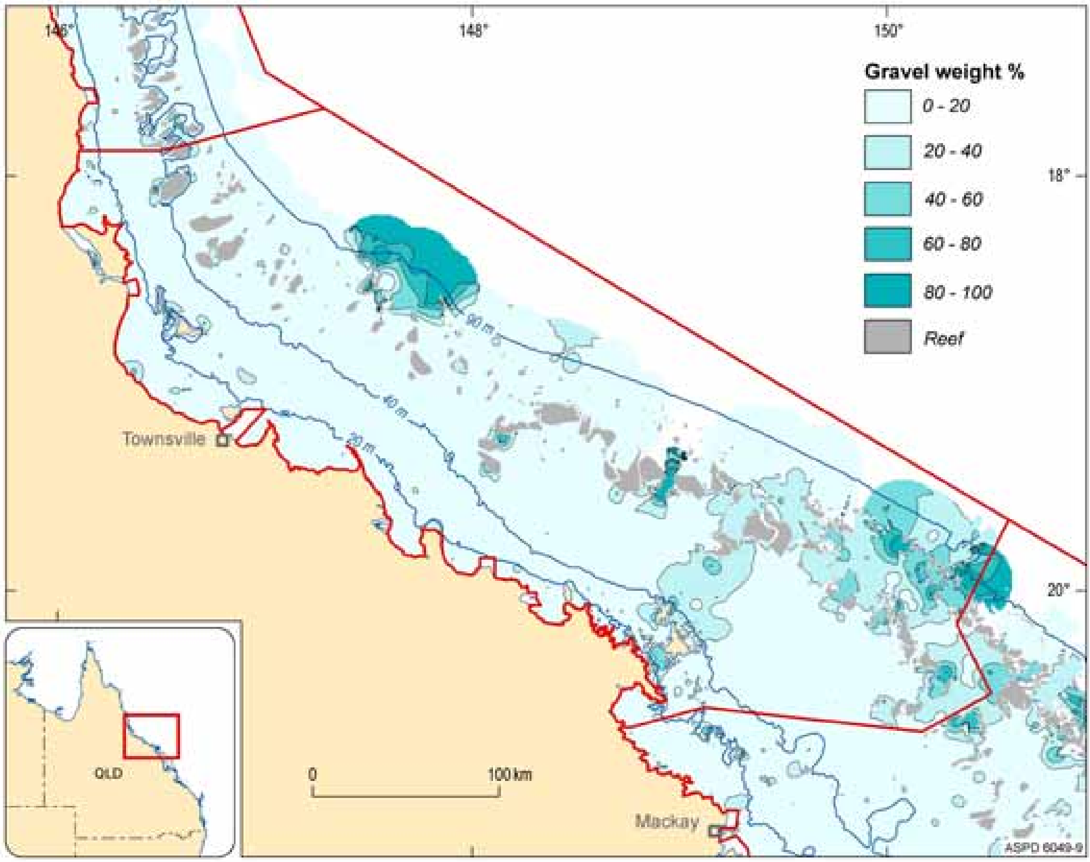

Figure 8.3. Percent gravel in the Townsville-Whitsunday Management Area.

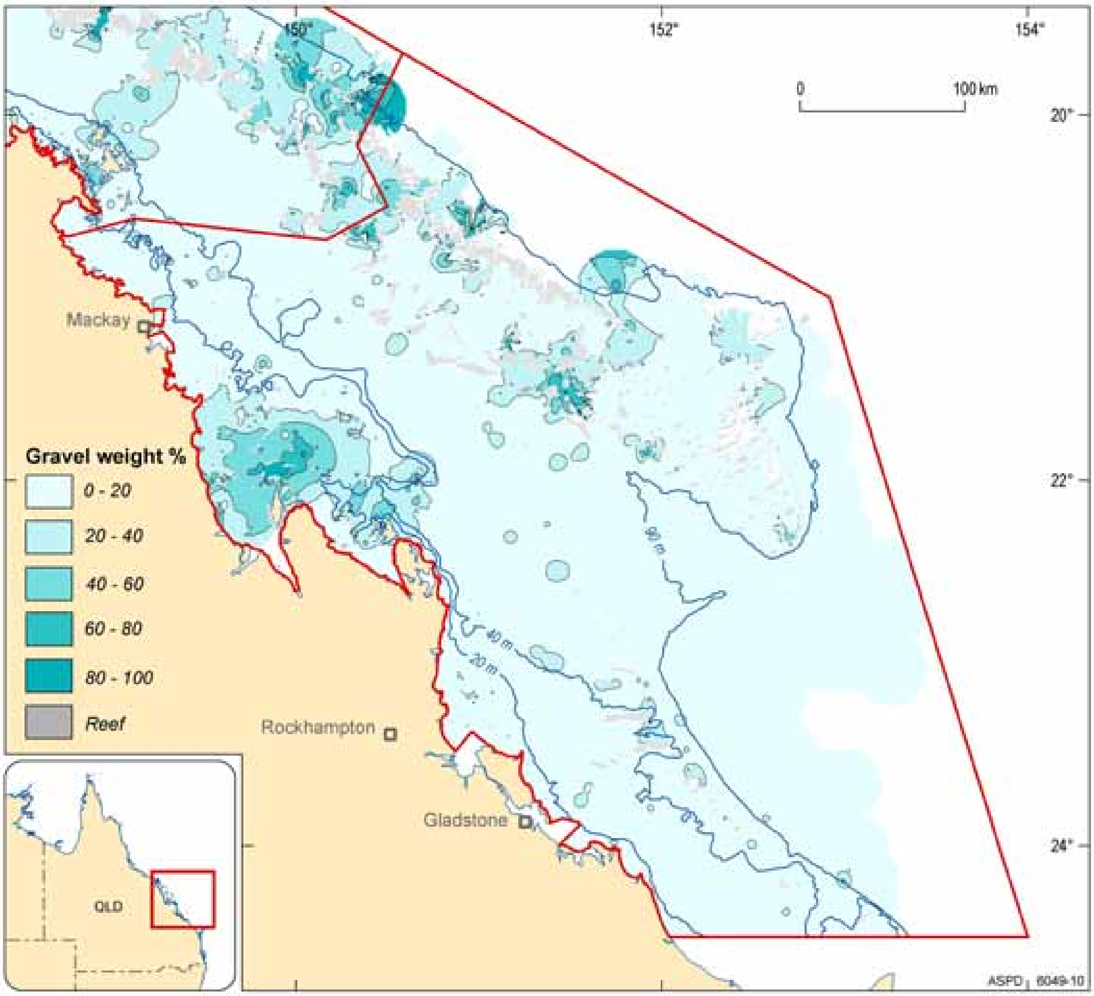

Figure 8.4. Percent gravel in the Mackay-Capricorn Management Area.

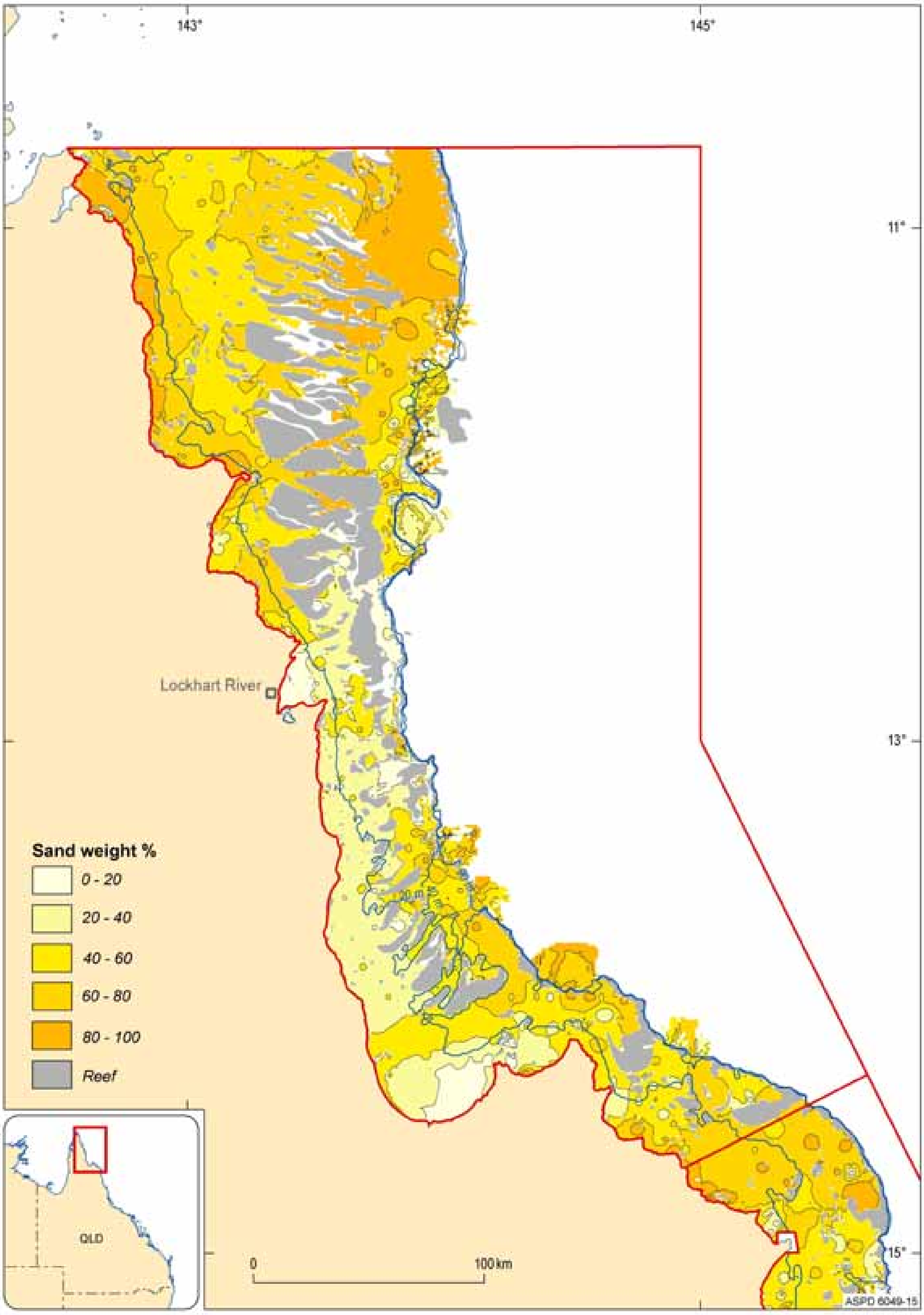

Figure 8.5. Percent sand in the Far Northern Management Area.

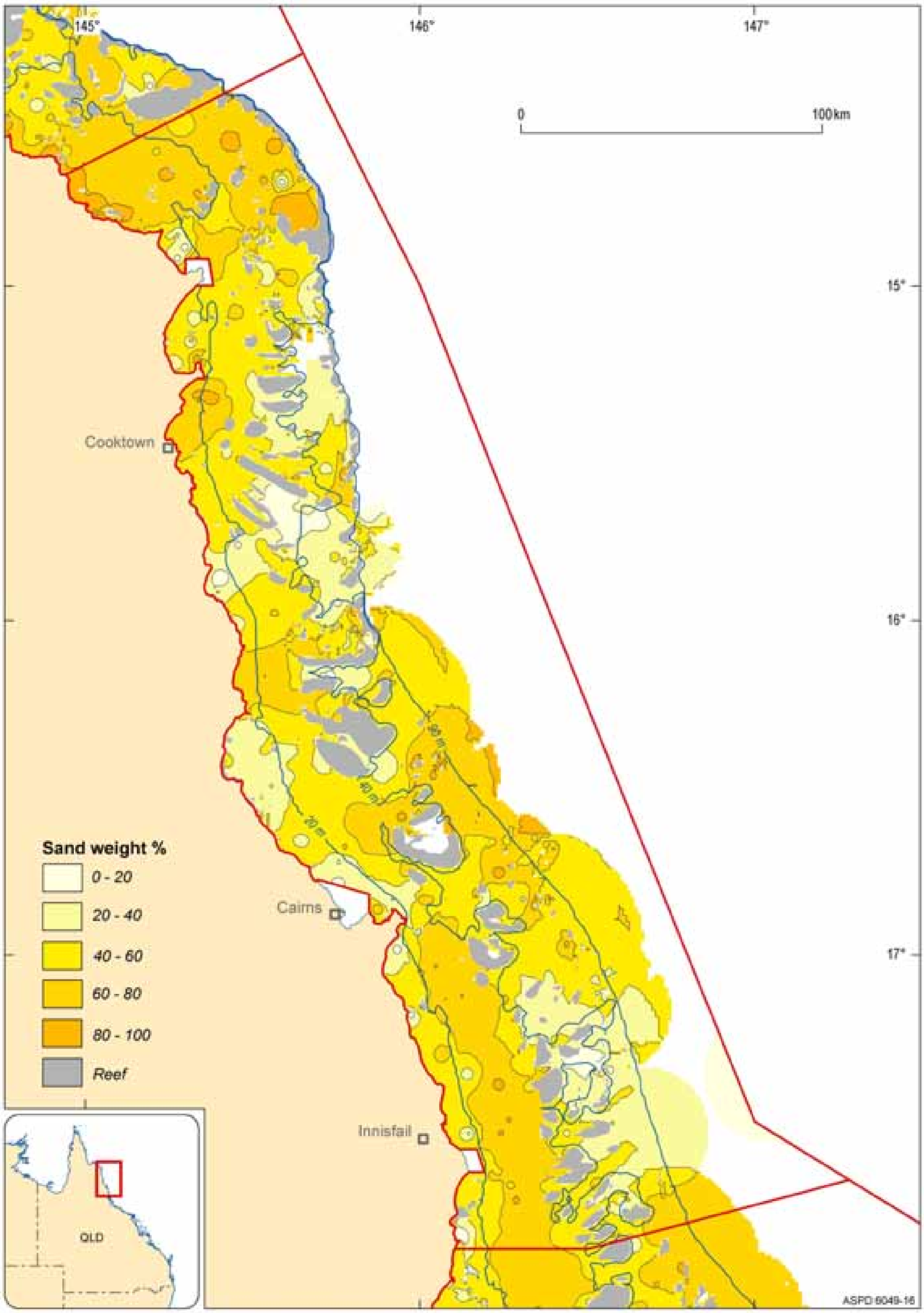

Figure 8.6. Percent sand in the Cairns-Cooktown Management Area.

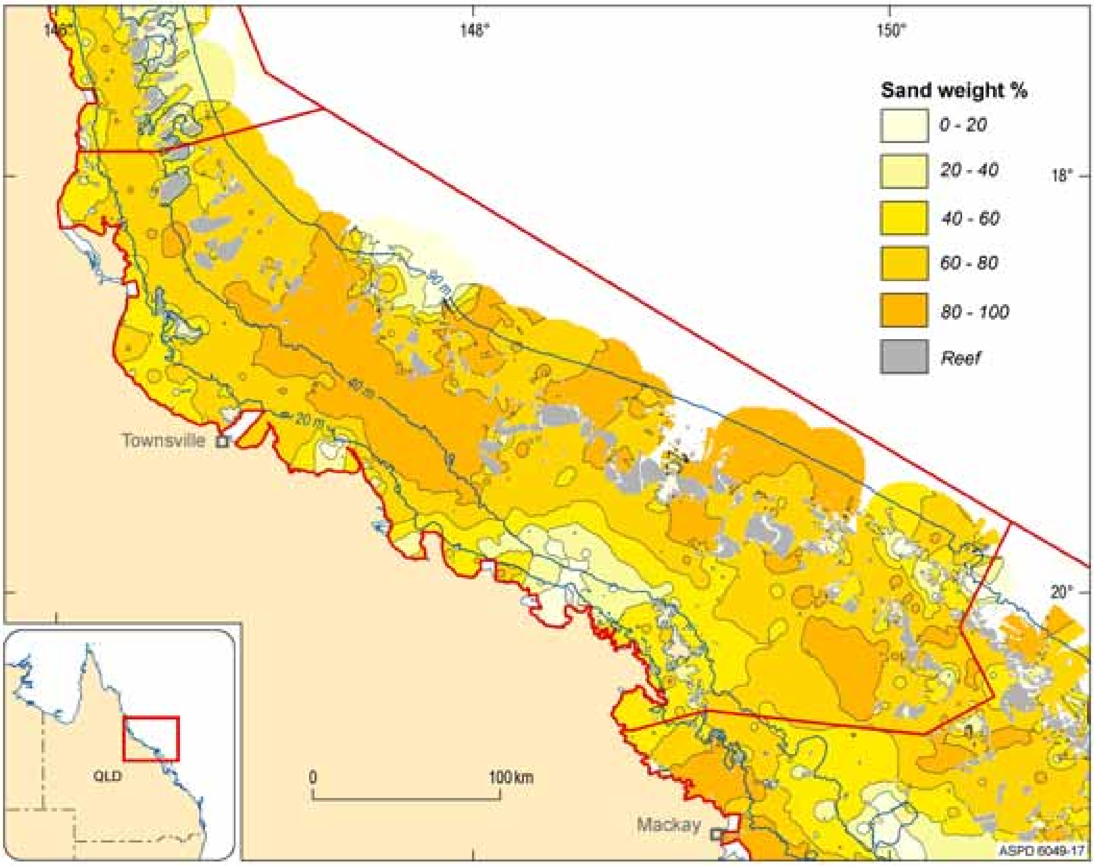

Figure 8.7. Percent sand in the Townsville-Whitsunday Management Area.

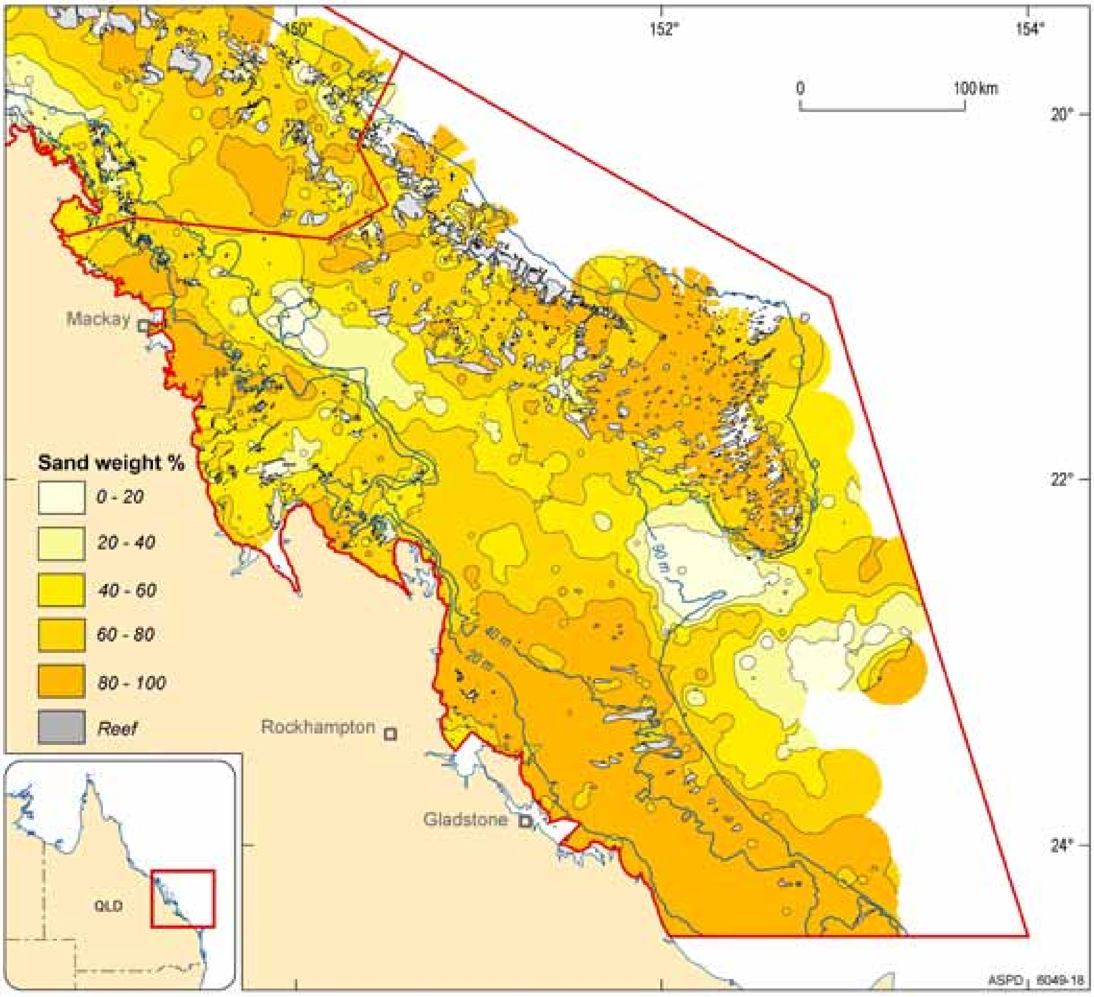

Figure 8.8. Percent sand in the Mackay-Capricorn Management Area.

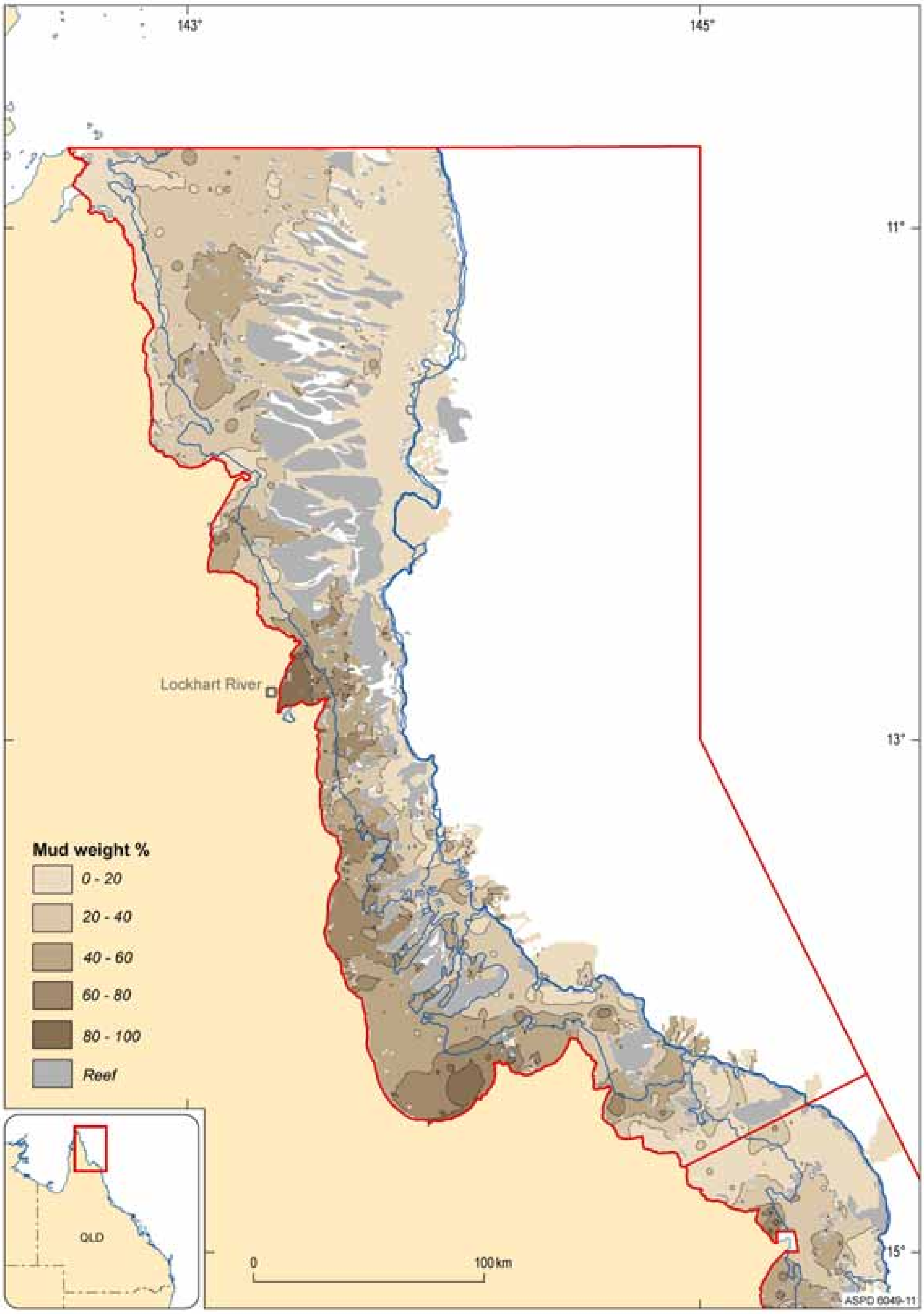

Figure 8.9. Percent mud in the Far Northern Management Area.

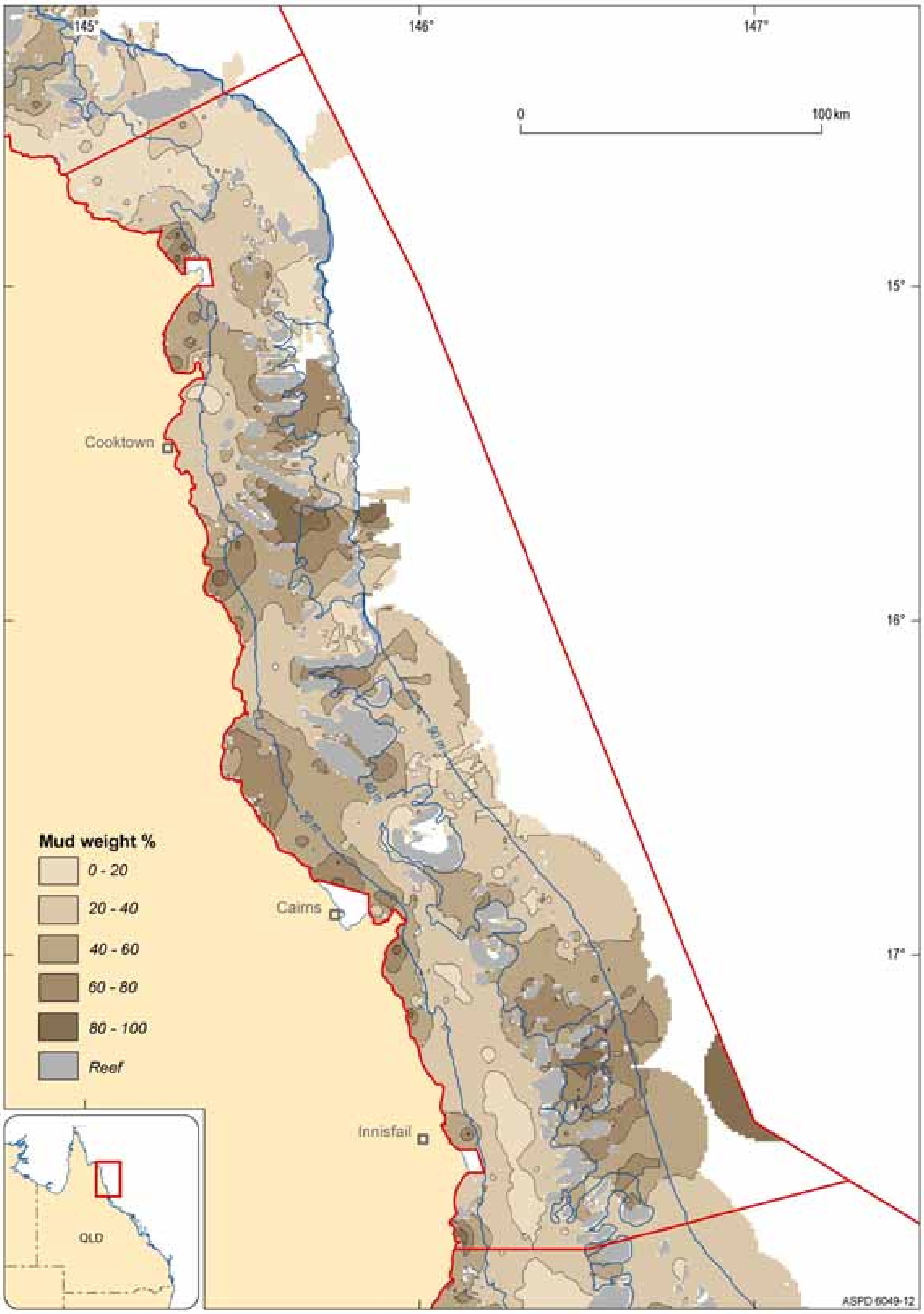

Figure 8.10. Percent mud in the Cairns-Cooktown Management Area.

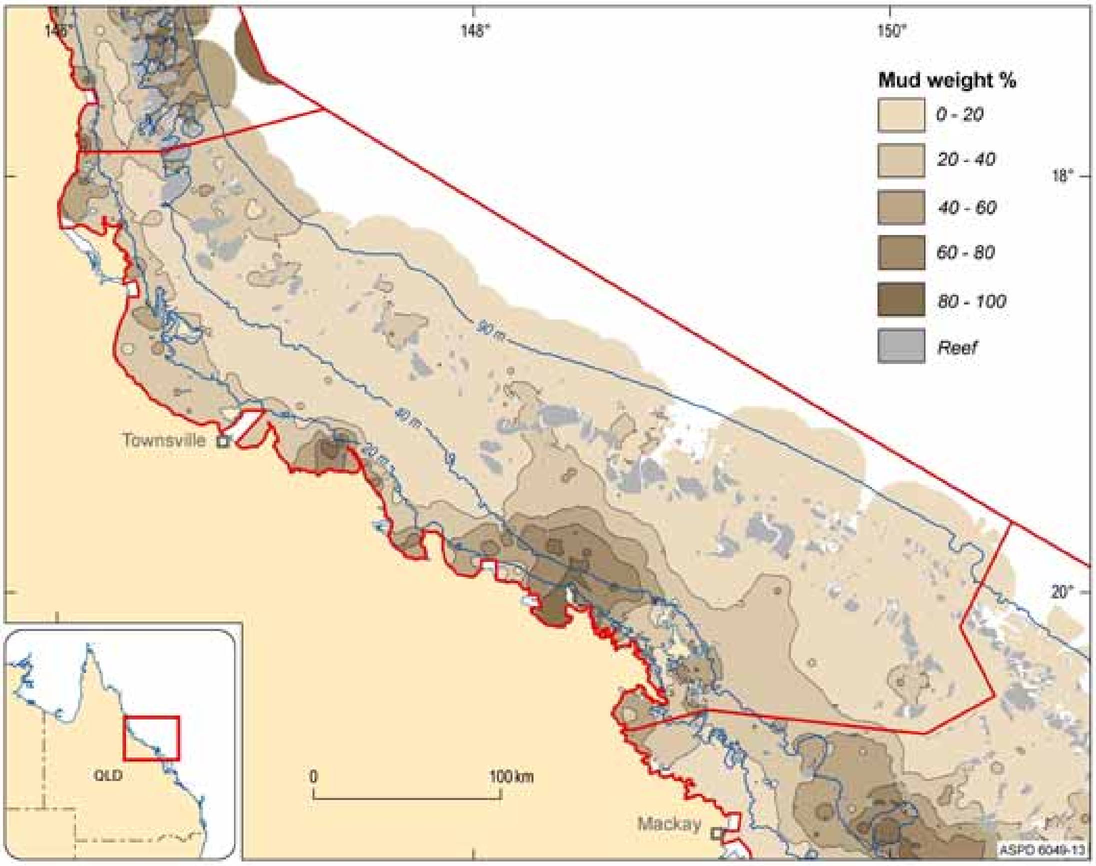

Figure 8.11. Percent mud in the Townsville-Whitsunday Management Area.

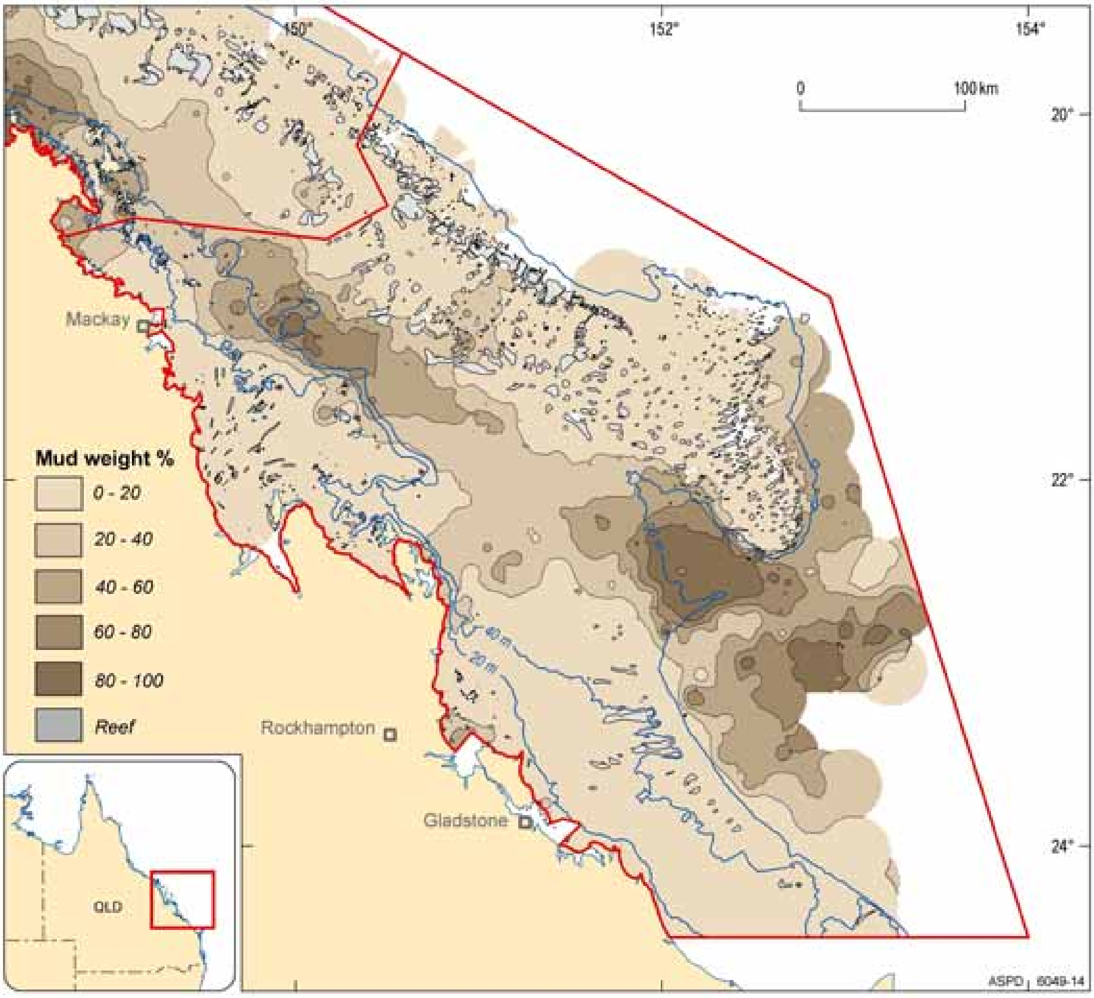

Figure 8.12. Percent mud in the Mackay-Capricorn Management Area.

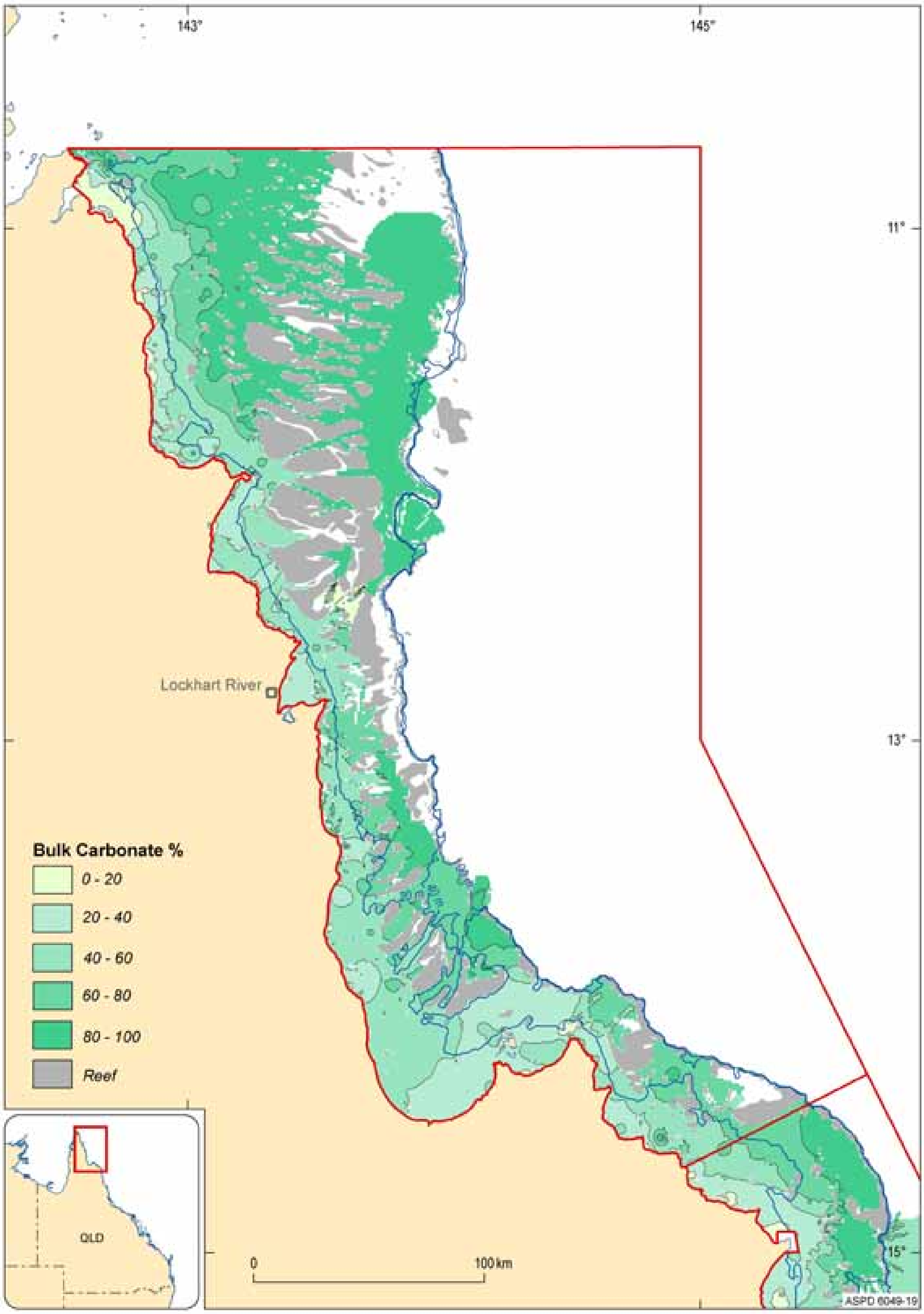

Figure 8.13. Percent bulk carbonate in the Far Northern Management Area.

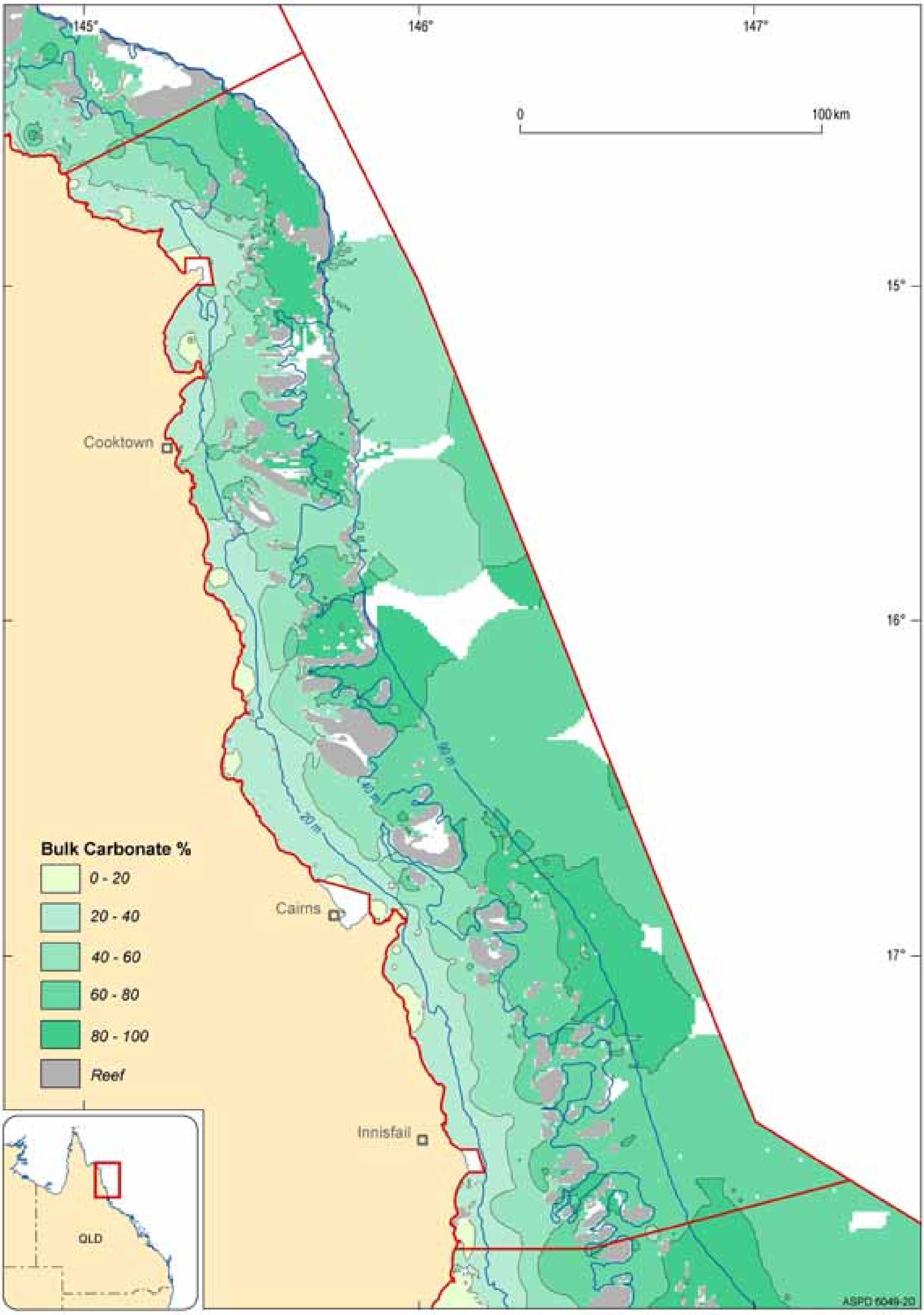

Figure 8.14. Percent bulk carbonate in the Cairns-Cooktown Management Area.

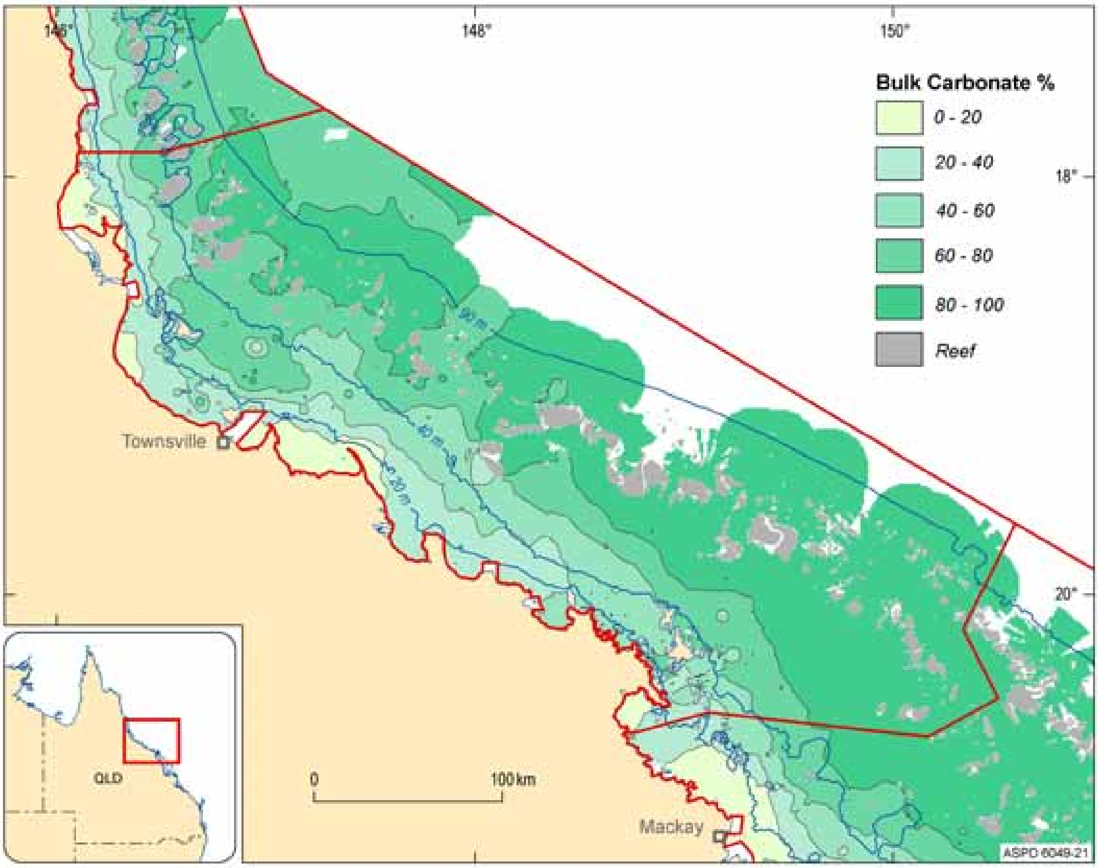

Figure 8.15. Percent bulk carbonate in the Townsville-Whitsunday Management Area.

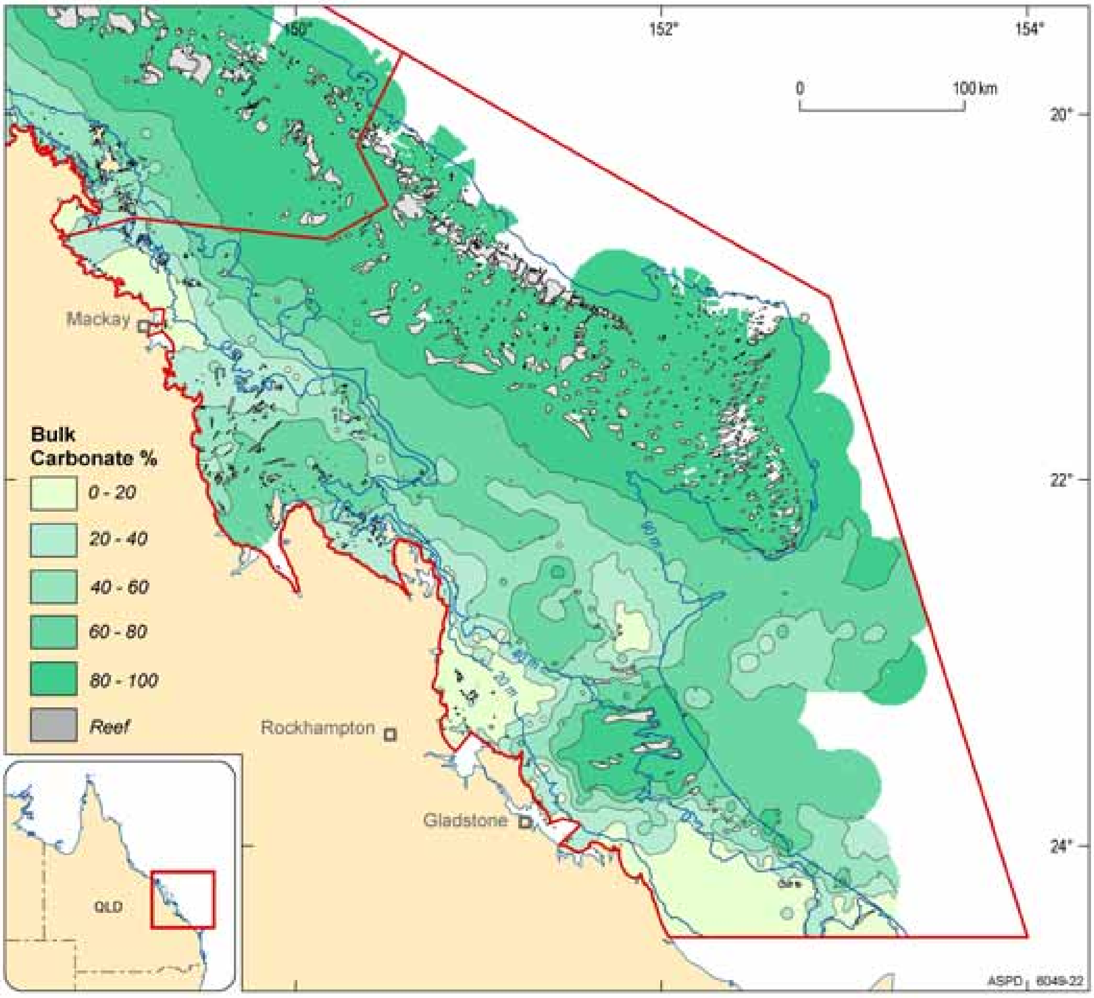

Figure 8.16. Percent bulk carbonate in the Mackay-Capricorn Management Area.

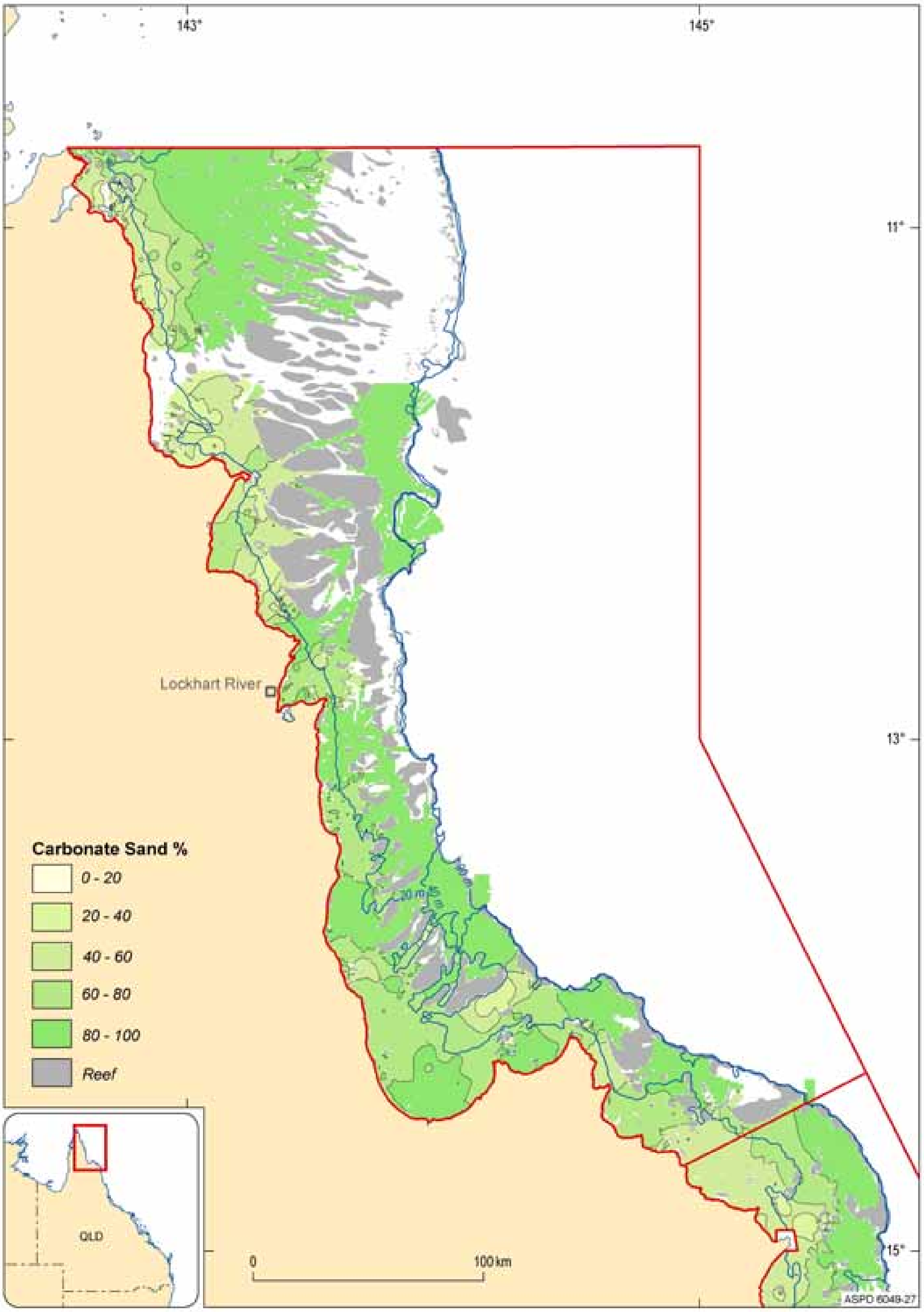

Figure 8.17. Percent carbonate sand in the Far Northern Management Area.

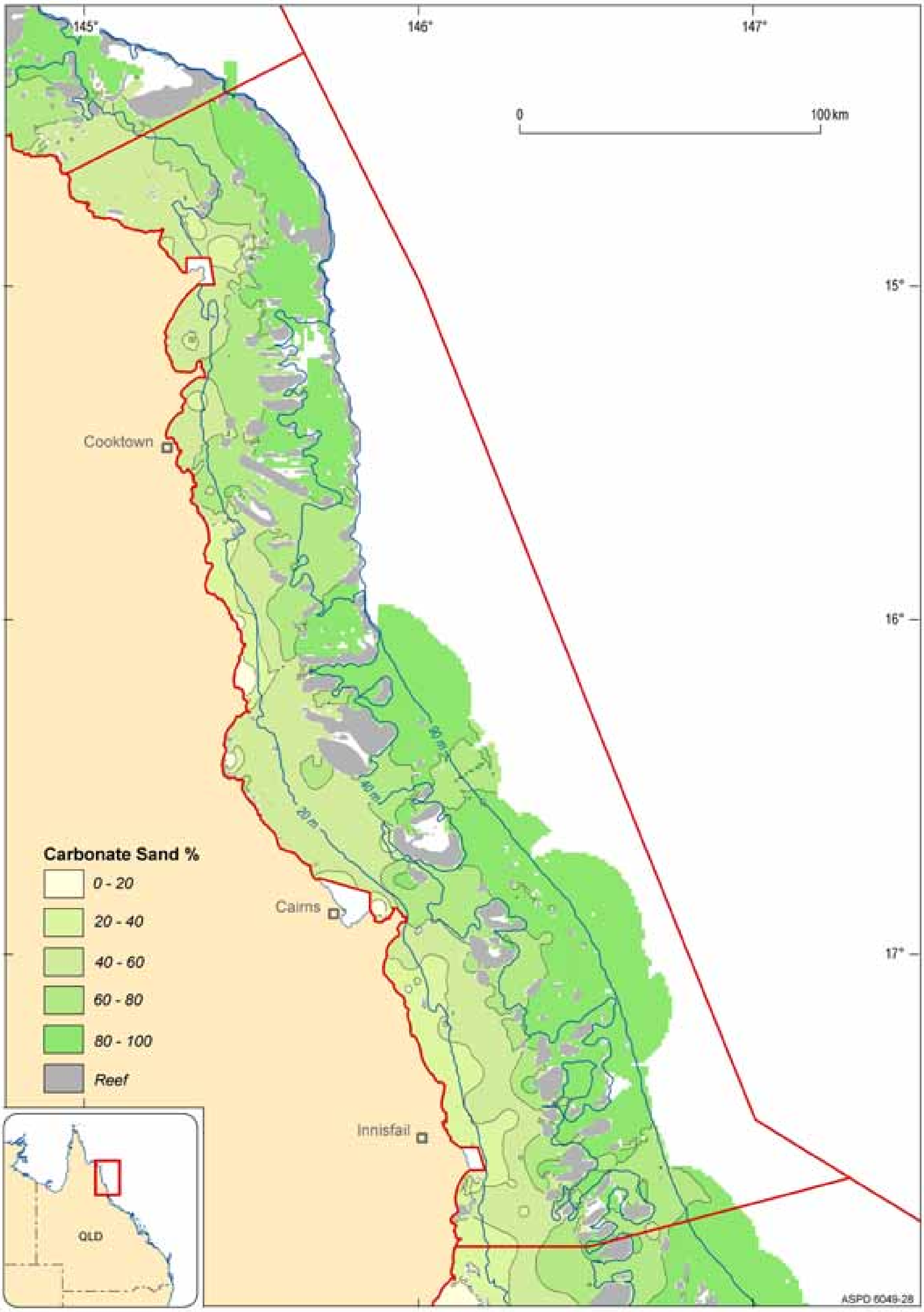

Figure 8.18. Percent carbonate sand in the Cairns-Cooktown Management Area.

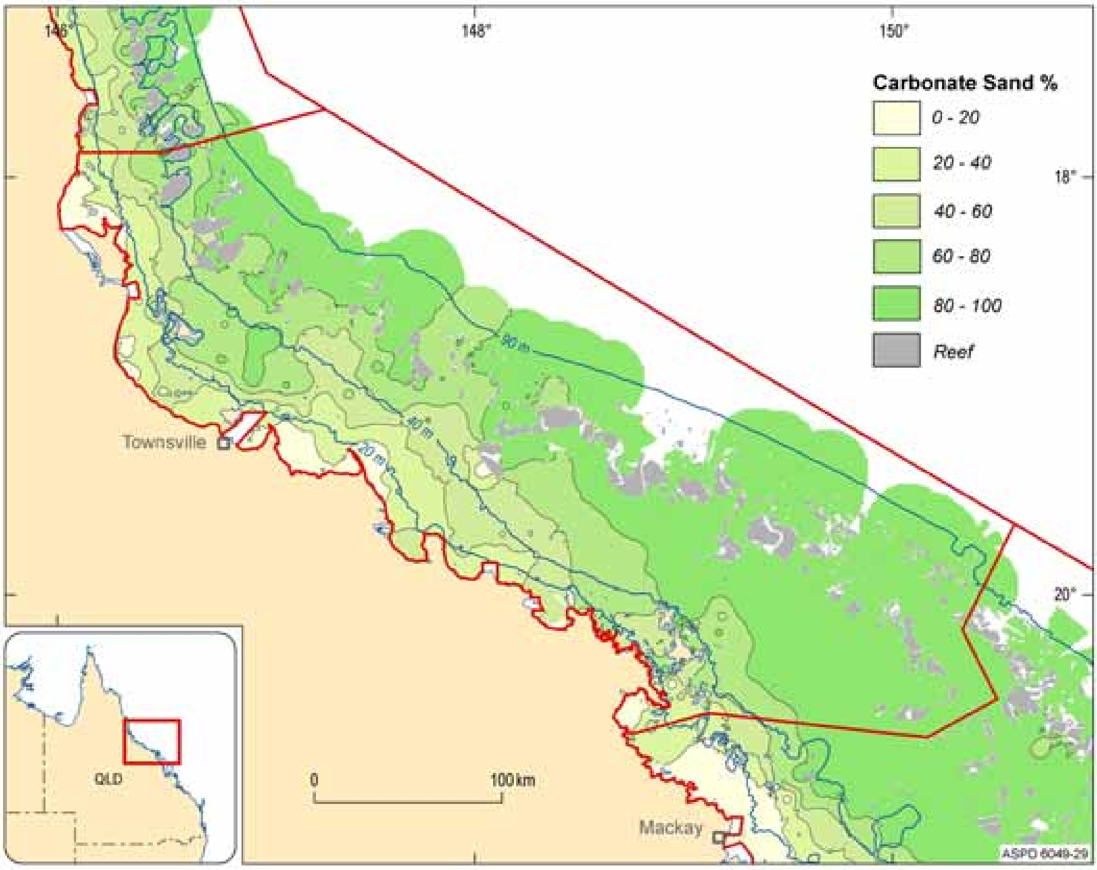

Figure 8.19. Percent carbonate sand in the Townsville-Whitsunday Management Area.

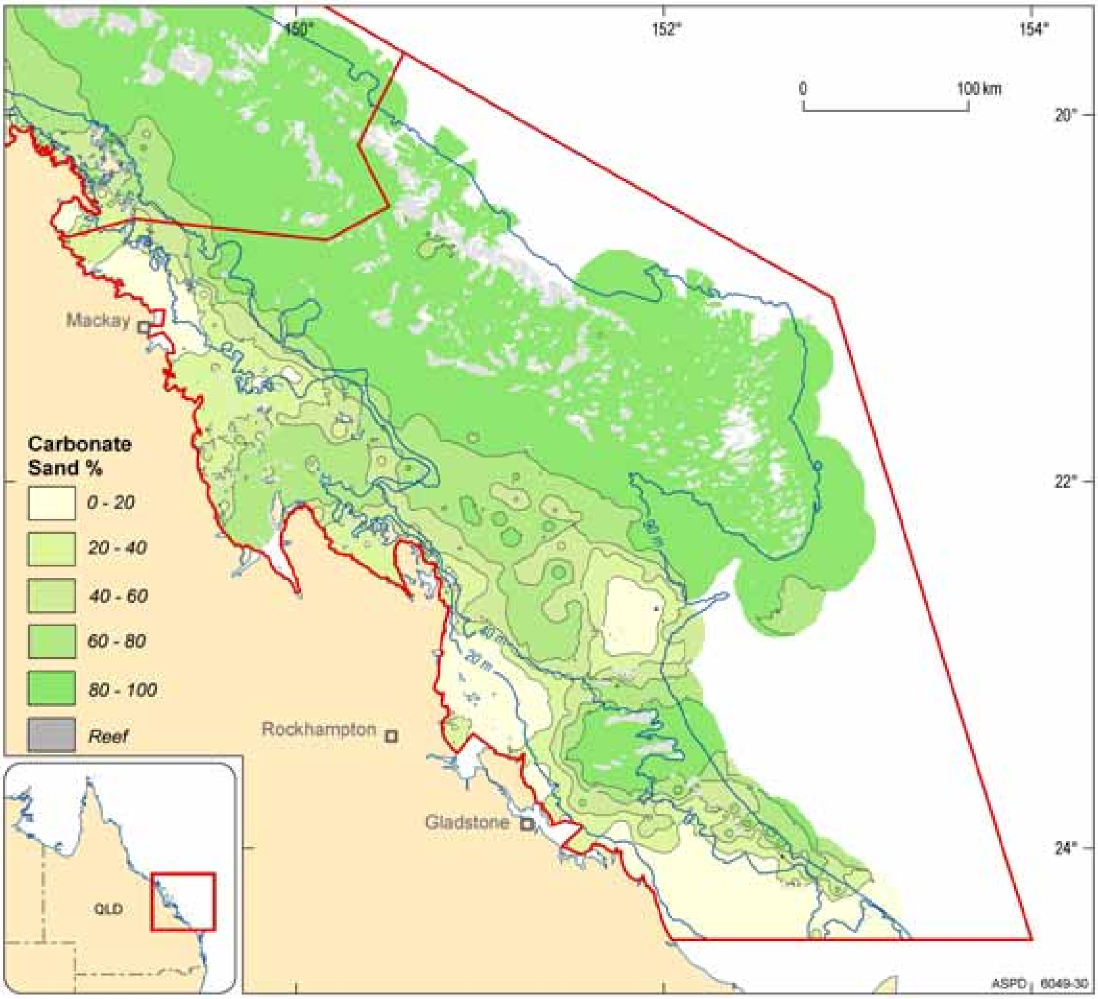

Figure 8.20. Percent carbonate sand in the Mackay-Capricorn Management Area.

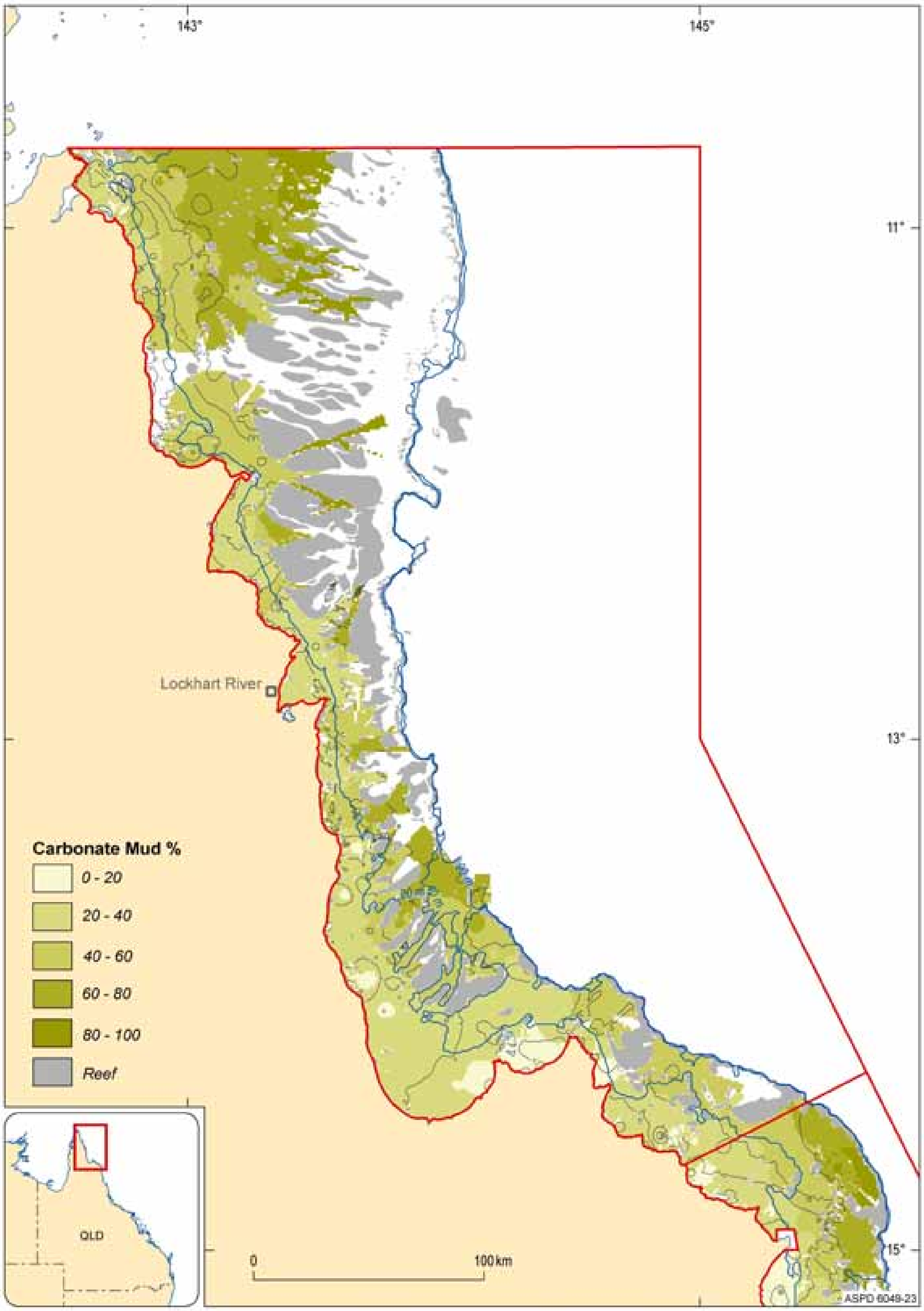

Figure 8.21. Percent carbonate mud in the Far Northern Management Area.

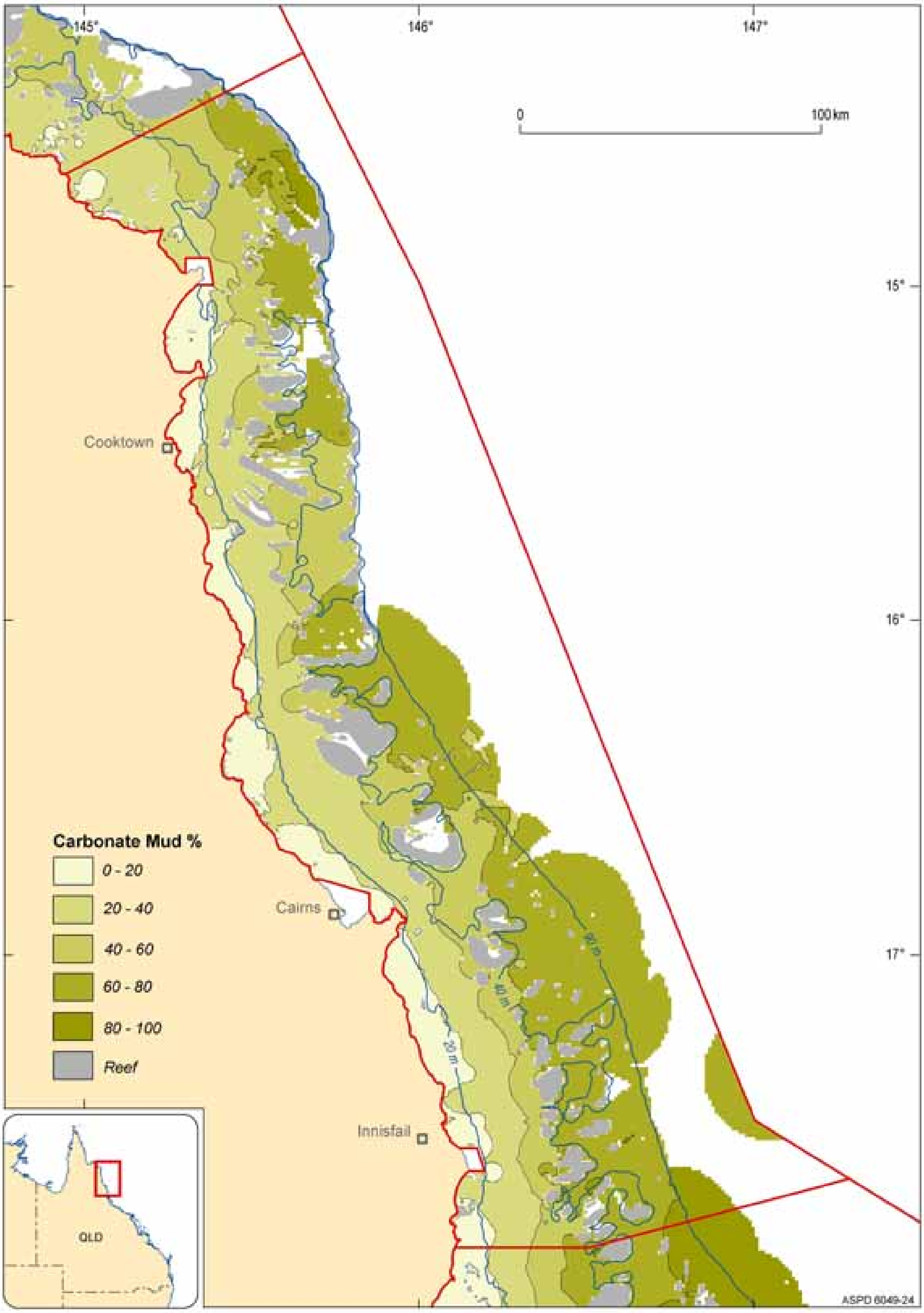

Figure 8.22. Percent carbonate mud in the Cairns-Cooktown Management Area.

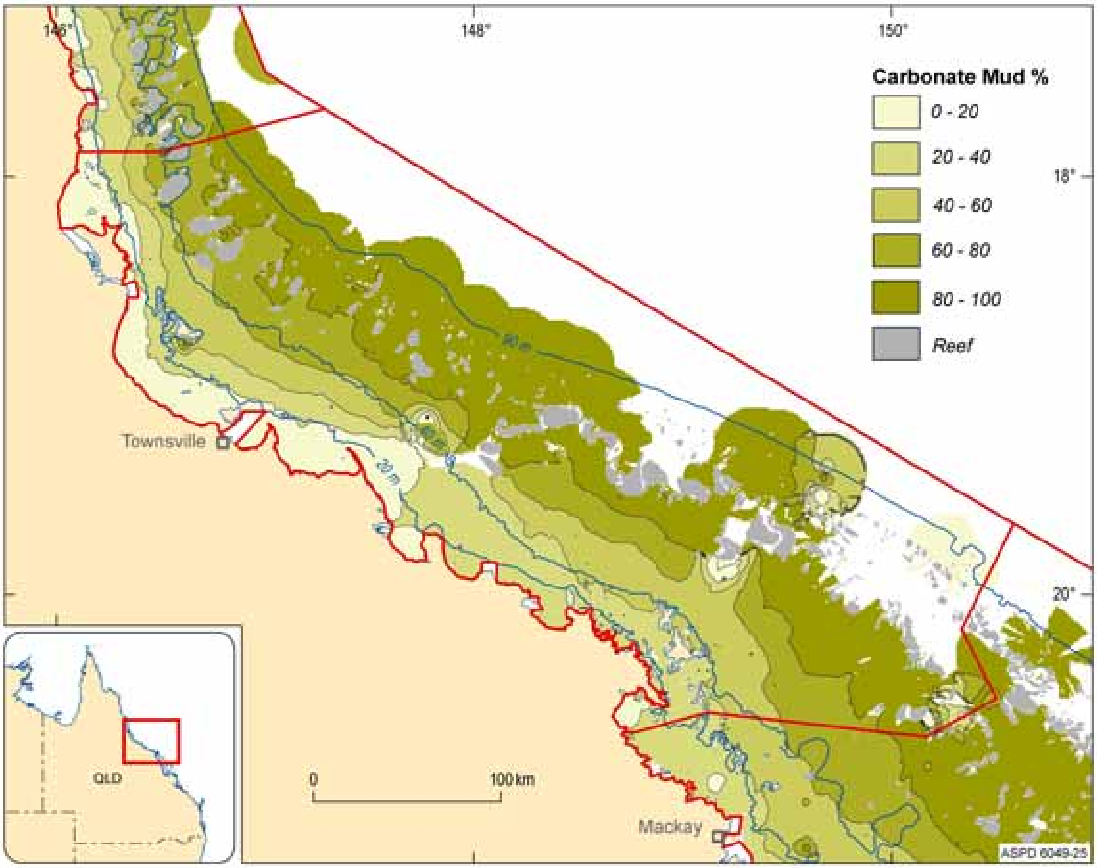

Figure 8.23. Percent carbonate mud in the Townsville-Whitsunday Management Area.

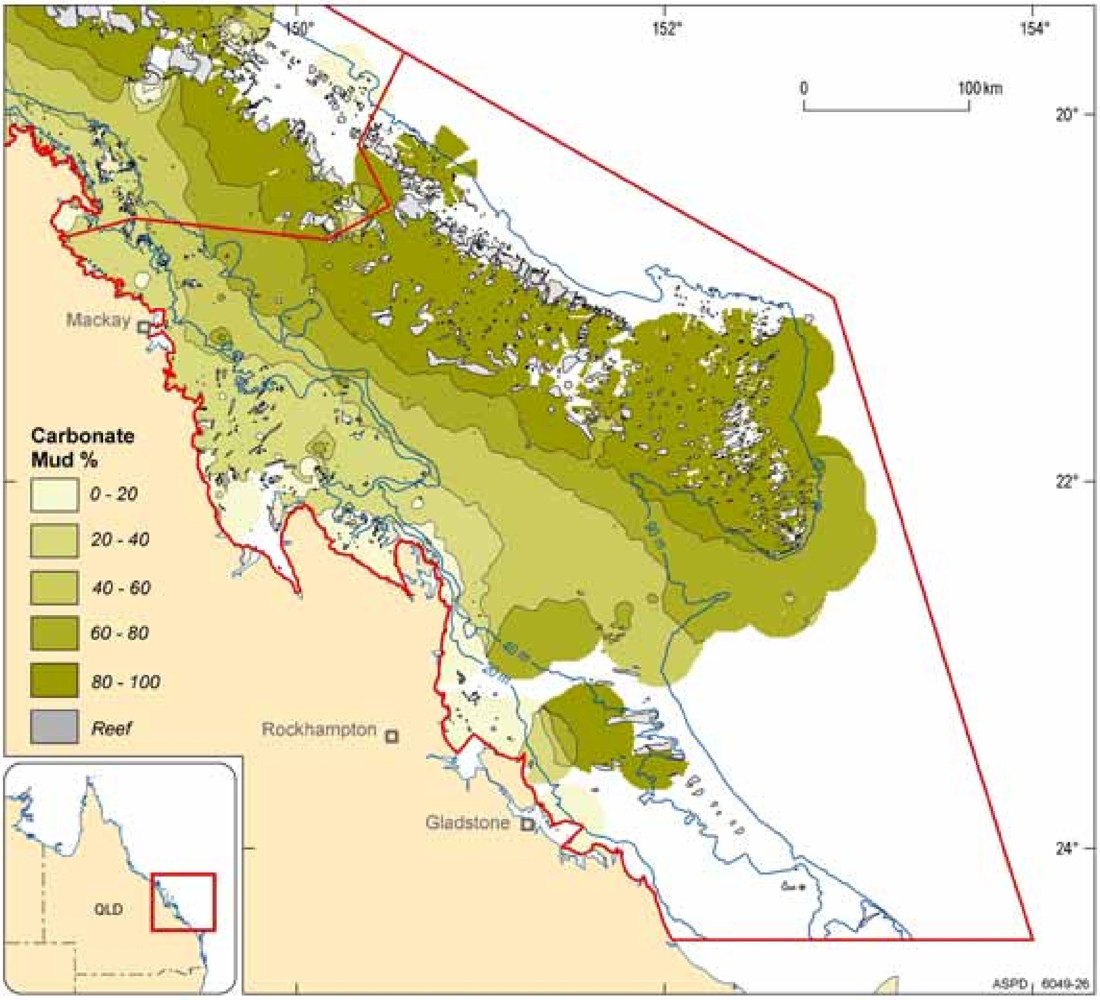

Figure 8.24. Percent carbonate mud in the Mackay-Capricorn Management Area.

8.2. Appendix B - Folk classification statistics

Tables of statistics are provided on the data CD-ROM in spreadsheet format.

8.3. Appendix C - Laser grain size results

The complete results of the laser grain size analysis for the AIMS samples are provided in Adobe PDF documents on the data CD-ROM.

8.4. Appendix D – Sieve grain size and carbonate results

The textural and compositional results for the AIMS samples are provided in spreadsheet format on the data CD-ROM. Each table is shown in a tab of the Excel workbook.

8.5. Appendix E - Sediment statistics of the seabed

Calculated statistics of the kilometre and percentage area of the sediment attributes for each seabed region (e.g. inner, middle and outer shelf, and continental slope) are provided in tables on the data CD-ROM.

8.6. Appendix F – Total areas

Tables of the total areas of each part of the shelf (inner, middle, outer) and continental slope that were used in the statistical calculations, and of information about the Marine Park planning zones, are provided on the data CD-ROM in word format.

8.7. Appendix G – Sediment statistics for each of the planning zones

Calculated statistics of the kilometre and percentage area of the sediment attributes for the planning zone types are provided in tables on the data CD-ROM.

8.8. Appendix H - Sediment attributes in planning zones

Comparative pie charts of the percentage area of each sediment attribute occurring in each of the planning zone types are provided on the data CD-ROM.

8.9. Appendix I – Detailed analysis of each planning zone type

We have included an additional detailed analysis of the sedimentary and geomorphic characteristics of each planning zone type, along with graphs and tables of physical data, provided in tables on the data CD-ROM.

8.9. ANALYSIS OF EACH PLANNING ZONE TYPE

8.9.1. Scientific Research Zone (SRZ)

SRZ occur on the inner, middle and outer shelf, and cover a small portion of the upper continental slope/shelf edge. They include a range of seabed environments from shallow water and nearshore regions (e.g. Cape Ferguson, Townsville; Palm Islands), reefs (e.g. Capricorn-Bunker Group) and shelf edge and upper slope (e.g. north-east off Cape Flattery) (Fig. 1.1; Appendix J).

Sediments:— The sediment characteristics of SRZ across the Marine Park comprise low overall gravel and mud concentrations. Gravel concentrations in these zones range from 2% to 65% and have a mean of 11% (Table 5.1). Low gravel concentrations of <20% dominate these zones and cover 77 km² (94%) of the total area of SRZ (Fig. 8.35).

Sand concentrations range from 30% to 96% and have a mean of 79% (Table 5.1). High sand concentrations of >60% dominate the seabed in these zones and cover 80 km² or more than 95% of the total area of SRZ (Fig. 8.35). Concentrations of >60% sand covers the greatest percentage area of all the planning zones (Appendix G).

Mud concentrations range from 0% to 41% and have a mean of 9% (Table. 5.1). Low mud concentrations of <20% dominate the seabed in SRZ and cover 60 km² (77%) of the total area of SRZ (Fig. 8.35). At 77%, concentrations of <20% mud cover the largest the largest percentage area compared to the other planning zones (Appendix G). All mud contents are less than 60% in this zone.

Bulk carbonate concentrations range from 12% to 93% and have a mean of 78% (Table 5.2). High bulk carbonate concentrations of >80% dominate the seabed in SRZ and cover 60 km² (68%) of the total area. At 68%, SRZ's contain the highest percentage area of >80% bulk carbonate out of the seven different zones (Appendix G). Low bulk carbonate concentrations of <40% cover a small proportion of the total area, at only 5 km² (7%).

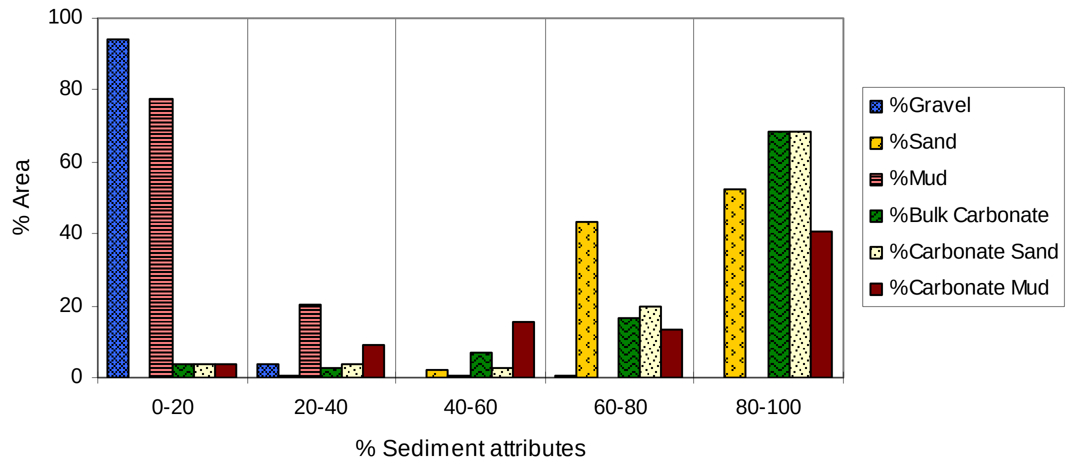

Figure 8.35. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Scientific Research Zones.

Carbonate sand concentrations range from 11% to 93% and have a mean of 79% (Table 5.2). High carbonate sand concentrations of >60% dominate the seabed in SRZ, covering 70 km² or more than 80% of the total area (Fig. 8.35). At 88%, concentrations of >60% carbonate sand cover the largest percentage area compared to the other planning zones (Appendix I).

Carbonate mud concentrations range from 8% to 84% and have a mean of 67% (Table 5.2). High carbonate mud concentrations of >80% dominate the seabed in SRZ's and cover 34 km² (41%) of the total area of SRZ (Fig. 8.35). Concentrations of >80% carbonate mud covers the highest percentage area, compared to the other planning zones (Appendix H).

Geomorphology:— The seabed geomorphology is dominated by reef, shelf and bank/shoal features and a small slope component, which together cover an area of 150 km² (Appendix J). Overall, SRZ contain four different geomorphic feature types, which is the lowest range of features found in the seven planning zones.

Reefs dominate the seabed in these zones and cover 70 km² (46%) of the total area of SRZ (Table 8.24). This area is 1.4 times greater than the area covered by the second most extensive feature in this zone, shelf environments. Reefs cover the largest percentage area out of all the planning zones, but number 11 in total, which is the lowest amount that occurs in any zone (Table 8.24).

Shelf features cover an area of 50 km² (31%) of the total area of SRZ (Table 8.24). Shelf features are the second most extensive and cover an area that is 1.4 times greater than the area covered by the third most extensive feature, bank/shoals. Shelf features cover the second lowest percentage area out of the planning zones. Shelf features number 15, which is the lowest amount of shelf in any zone (Table 8.24).

Bank/shoals cover an area of 30 km² (22%) of the total area of SRZ, an area that is 34 times greater than the area covered by slope features in these zones. Bank/shoals are the third most extensive in SRZ and cover the highest percentage area out of all seven planning zones (Table 8.24). Bank/shoals number 4, which is the lowest amount of bank/shoals occurring in any zone (Table 8.24).

Slope features cover an area of less than 1% or <5 km² of the total area of SRZ (Table 8.24). Slope features cover an area that is 70 times smaller than the area covered by reefs in SRZ. Slope features cover the lowest percentage area out of all planning zones (Table 8.24). Slope features number 5, which is the lowest amount occurring in any of the different planning zones.

Table 8.24. Area of geomorphic features that comprise the Scientific Research Zones (SRZ).

Geomorphic Features	**Kilometre²*	*Percent*	*Count*
Reef	70	46	11
Shelf	50	31	15
Bank/Shoals	30	22	4
Slope	<5	<1	5
Total:	150	100	35

*Rounded to the nearest 10 km²

8.9.2. Preservation zone (PZ)

PZ occur on the inner, middle and outer shelf, and the continental slope, with the majority of PZ occurring on the outer shelf. Seabed environments range from the nearshore (e.g. near Cape Melville), reefs (e.g. Carter Reef), inter-reefal (e.g. Swains Reefs), and continental slope regions (e.g. offshore Cape Grenville) (Fig. 1.1; Appendix J).

Sediments:— Seabed sediments in PZ are characterised by low overall gravel and mud concentrations and high bulk and sand carbonate concentrations. Gravel concentrations in PZ range from 1% to 89% and have a mean of 13% (Table 5.1). Low overall gravel concentrations of <20% cover 320 km² (66%) of the total area (Appendix G; Fig. 8.36). Compared to the other planning zones, at 66%, the percentage area of <20% gravel concentrations is the fourth largest.

Sand concentrations range from 7% to 98% and have a mean of 64% (Table 5.1). High overall sand concentrations of >60% cover 270 km² (55%) of the total area of PZ's (Appendix G; Fig. 8.36). Compared to the other planning zones, at 55%, the percentage area of >60% sand concentrations covers the third largest area. Low sand concentrations of <20% only cover a small area of <5 km² (<1%) of PZ's, which is the lowest of all the planning zones.

Mud concentrations range from 0% to 75% and have a mean of 22% (Table 5.1). Low overall mud concentrations of <20% cover 240 km² (50%) of the total area of PZ's (Appendix G, Fig. 8.36). Covering 50% of the total area, concentrations of <20% mud covers second largest percentage area compared to the other planning zone types. This zone contains no mud concentrations >80%.

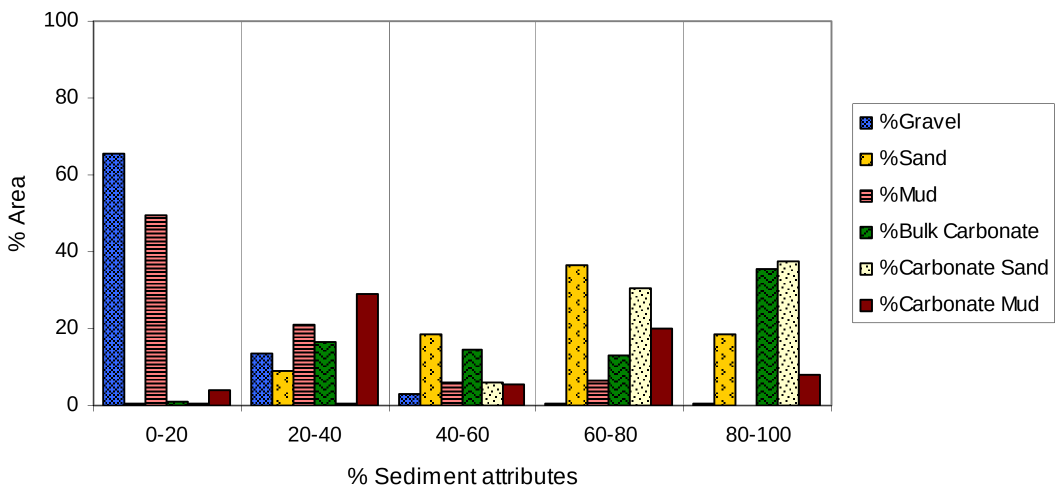

Figure 8.36. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Preservation Zones.

Bulk carbonate concentrations range from 15% to 99% and have a mean of 67% (Table 5.2). High bulk carbonate concentrations of >60% dominate the seabed in PZ's and cover 230 km² (48%) of the total area of PZ's (Appendix G; Fig 8.36). Covering 48% of the total area, concentrations of >60% bulk carbonate cover the fourth largest percentage area compared to the other planning zone types. Bulk carbonate concentrations of <20% cover <10 km² (<5%) of this zone.

Carbonate sand concentrations range from 11% to 97% and have a mean of 78% (Table 5.2). High carbonate sand concentrations of >60% dominate the seabed in PZ and cover 330 km² (67%) of the total area of PZ's (Appendix G, Fig 8.36). Covering 67% of the total area, concentrations of >60% carbonate sand cover the second largest percentage area compared to the other planning zone types. Carbonate sand concentrations of <40% cover a small proportion of the total area, at <10 km² (<5%).

Carbonate mud concentrations range from 0% to 94% and have a mean of 48% (Table 5.2). Carbonate mud concentrations of <40% dominate the seabed in PZ's and cover 160 km² (33%) of the total area of PZ (Appendix G; Fig 8.36). Covering 33% of the total area, concentrations of <40% carbonate mud cover the second largest percentage area compared to the other planning zones. Carbonate mud concentrations of >80% cover 40 km² (<10%) of the total area.

Geomorphology:— Overall, PZ include seven geomorphic feature types (Table 8.25). The seabed geomorphology is comprised of three main features: shelf, reef, and plateau, and four other features: slope, bank/shoals, terrace, and deep/hole/valley, which together cover a total area of 710 km² (Table 8.25; Appendix J).

Shelf features make up the greatest proportion of seabed environments, covering 300 km² (43%) of the total area of PZ's (Table 8.25). Shelf features are the most extensive and cover an area that is 10 times greater than the area covered by the fourth most extensive feature, the slope. A total of 32 shelf features occur in the PZ (Table 8.25).

Reefs cover an area of 220 km² (31%) of the total area of PZ (Table 8.25). Reefs are the second most extensive feature and cover an area that is 7.8 times greater than the area covered by the fifth most extensive feature, bank/shoals. A total of 49 reefs occur in the PZ, which is the second lowest of all the planning zones.

Plateaus cover an area of 90 km² (13%) of the total area (Table 8.25). Plateaus are the third most extensive feature and cover an area that is 3.2 times greater than the area covered by slope features. A total of 16 plateaus occur in PZ, which is the lowest of all the planning zones.

Table 8.25. Area of geomorphic features occurring within the Preservation Zones (PZ).

Geomorphic Features	**Kilometre²*	*Percent*	*Count*
Shelf	304	43	32
Reef	222	31	49
Plateau	91	13	16
Slope	28	4	7
Bank/Shoals	28	4	5
Terrace	19	3	1
Deep/Hole/Valley	14	2	7
Total:	710	100	117

*Rounded to the nearest 10 km²

Together, the slope, bank/shoals, terrace and deep/hole/valley environments make up a small proportion of the total area, and individually cover <5% of PZ (Table 8.25). These features also make up a small proportion of the other planning zones in the Marine Park.

8.9.3. Conservation Park Zone (CRZ)

CRZ occur on the inner, middle and outer shelf, with the majority occurring between 0 and 40 m water depth on the inner and middle shelves. Seabed environments range from shallow nearshore (e.g. Bathurst Bay, Cleveland Bay), inter-island (e.g. Palm Island, Whitsunday Islands) and reefs (e.g. Davies Reef, Hook Reef) (Fig. 1.1; Appendix J).

Sediments:— Seabed sediments in CRZ are characterised by low overall gravel and mud concentrations and high sand and carbonate sand contents (Fig. 8.37). Gravel concentrations in CRZ range from 0% to 60% and have a mean of 10% (Table 5.1). Low gravel concentrations of <20% cover 3,720 km² (85%) of the total area of CRZ (Fig 8.37; Appendix G). Covering 85% of the total area, concentrations of <20% gravel cover the third largest percentage area compared to the other planning zones. Gravel concentrations of >60% cover a small proportion of the total area of CRZ, at 1 km² (<1%).

Sand concentrations range from 6% to 99% and have a mean of 60% (Table 5.1). High sand concentrations of >60% cover 2,200 km² (50%) of the total area of CRZ (Fig 8.37; Appendix G). Covering 50% of the total area, concentrations of >60% sand cover the fourth largest percentage are compared to the other planning zones. Sand concentrations of <20% cover 140 km² (<5%) of the total area of CRZ (Fig. 8.37).

Mud concentrations range from 0% to 90% and have a mean of 30% (Table 5.1). Low mud concentrations of <40% cover 2,670 km² (61%) of the total area of CRZ (Fig. 8.37; Appendix G). Covering 61% of the total area, concentrations of <40% mud cover the fourth largest percentage area compared to the other planning zone typess. Mud concentrations of >80% cover 120 km² (<5%) of the total area of CRZ.

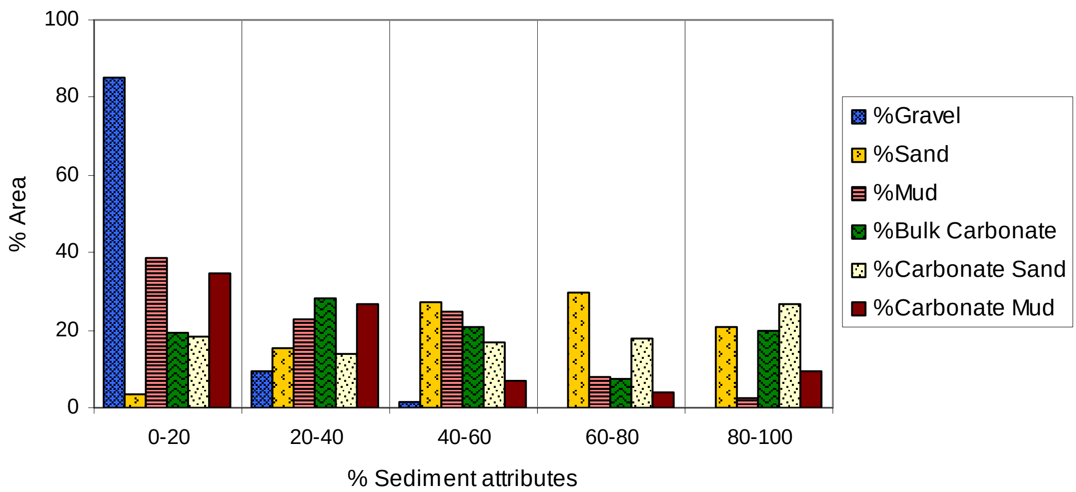

Figure 8.37. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Conservation Park Zones.

Bulk carbonate concentrations range from 1% to 97% and have a mean of 46% (Table 5.2). Bulk carbonate concentrations of 40-60% cover 920 km² (21%) of the total area of CRZ (Fig. 8.37). Low bulk carbonate concentrations of <40% dominate the seabed in CRZ and cover an area of 2,070 km² (47%) (Fig. 8.37). Covering 47% of the total area, the percentage area of <40% bulk carbonate has the greatest coverage out of the seven planning zones (Appendix H.)

Carbonate sand concentrations range from 2% to 95% and have a mean of 55% (Table 5.2). Carbonate sand concentrations of >60% dominate the seabed in CRZ and cover 1,950 km² (45%) (Fig. 8.37; Appendix G). Covering 45% of the total area, the area of >60% carbonate sand covers the second smallest percentage area compared to the other planning zones. Carbonate sand concentrations of <20% cover 810 km² (19%) of the total area (Fig. 8.37).

Carbonate mud concentrations range from 0% to 89% and have a mean of 32% (Table 5.2). Carbonate mud concentrations of <40% dominate the seabed in CRZ and cover 2,680 km² (61%) (Fig. 8.37; Appendix G). Covering 61% of the total area, the area of <40% carbonate mud covers the greatest percentage area out of the seven planning zones. Carbonate mud concentrations of >80% cover 420 km² (10%) of the total area of CRZ (Fig 8.37).

Geomorphology:— The seabed geomorphology is dominated by three major feature types: banks/shoals, reefs and shelf, and five minor geomorphic features: tidal-sandwave/sand-bank, saddle, terrace, basin and deep/hole/valley (Table 8.26; Appendix J). Together these features cover an area of 5,120 km² or 99% of the total area of CRZ.

Shelf features make up the greatest proportion of seabed environments occurring within CRZ, and cover 3,720 km² (72%) of the total area, which is 4.7 times greater than the next most extensive feature, reefs (Table 8.26). At 72%, shelf features cover the highest percentage area out of the seven planning zones and number 183 individual features.

Reefs cover an area of 780 km² (15%) of the total area (Table 8.26), which is 1.5 times greater than the area covered by the next most abundant feature, banks/shoals. Reefs cover the third highest area out of all the planning zones. Reefs number 284 individual features, which is the third highest of all the planning zones (Table 8.26).

Table 8.26. Area of geomorphic features occurring within the Conservation Park Zones (CRZ).

Geomorphic Features	**Kilometre^2*	*Percent*	*Count*
Shelf	3,720	72	183
Reef	780	15	284
Bank/Shoals	500	10	72
Deep/Hole/Valley	40	1	13
Basin	30	1	5
Terrace	20	<1	2
Saddle	20	<1	4
Tidal-sandwave/Sand-bank	10	<1	1
Total:	5,120	99	564

*Rounded to the nearest 10 km^2

Bank/shoals cover an area of 500 km² (10%) of the total area (Table 8.26). Bank/shoals cover an area that is 13 times greater than the area covered by deep/hole/valley features in CRZ's. Bank/shoals cover the second highest percentage area out of all the planning zones and number 72, which is the fourth highest of all the planning zones (Table 8.26).

The deep/hole/valley, basin, terrace, saddle, tidal-sandwave/sand-bank features individually occupy less than 1% of the total area of the CRZ (Table 8.26). The percentage area occupied by these environments in CRZ is amongst the lowest out of the seven different types of planning zones.

8.9.4. Buffer Zone (BZ)

BZ's occur on the middle and outer shelf, and continental slope, with the majority of the BZ occurring in water depths greater than 90 m on the continental slope. Seabed environments include reefs (e.g. Endeavour Reef, Aglncourt Reefs), and shelf edge and upper slope (e.g. offshore Cooktown, Townsville and Gladstone) (Fig 1.1; Appendix J).

Sediments:— Seabed sediments in BZ are characterised by low gravel and mud contents and high bulk carbonate concentrations (Fig. 8.38). Gravel concentrations range from 0% to 97% and have a mean of 21% (Table 5.1, Appendix G). Gravel concentrations of <20% dominate the seabed in BZ and cover 2,220 km^2 (22%) of the total area (Fig 8.38). Covering 22% of the total area, the area of <20% gravel in BZ covers the smallest percentage area out of the seven different planning zone types (Appendix H). Gravel concentrations of 20-80% cover 130 km^2 (1%) and concentrations of >80% cover 590 km^2 (6%) of the area (Fig. 8.38).

Sand concentrations range from 2% to 97% and have a mean of 46% (Table 5.1). Low sand concentrations of <40% dominate the seabed in BZ, covering 1,280 km^2 (13%) of the total area (Fig. 8.38; Appendix G). High sand concentrations of >60% cover 1,140 km^2 (12%) of the total area. The percentage area of >60% in BZ covers the smallest area out of the seven planning zones (Appendix H).

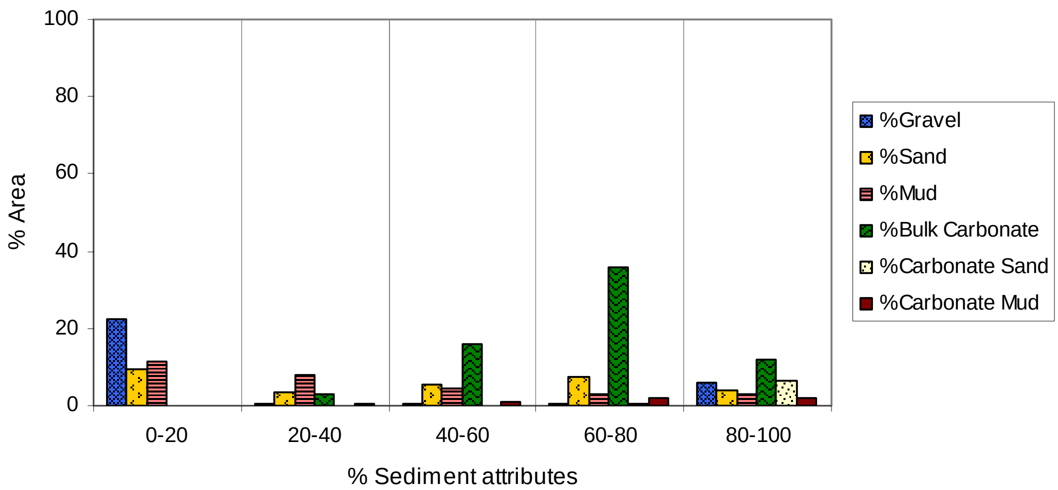

Figure. 8.38. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Buffer Zones.

Mud concentrations range from 0% to 90% and have a mean of 32% (Table 5.1). Low mud concentrations of <40% dominate the seabed in BZ and cover 1,920 km^2 (20%) of the total area (Fig. 8.38; Appendix G). Covering 20% of the total area, the area of <40% mud in BZ covers the smallest percentage area compared with the other planning zone types (Appendix H). High mud concentrations of >80% cover 290 km^2 (3%) (Fig. 8.38).

Bulk carbonate concentrations range from 28% to 95% and have a mean of 70% (Table 5.2). Bulk carbonate concentrations of >60% dominate the seabed in BZ and cover 4,720 km^2 (48%) of the total area (Fig. 8.38; Appendix G). Covering 48% of the total area, concentrations of >60% bulk carbonate cover the fourth largest percentage area compared to the other planning zone types. Low bulk carbonate concentrations of 20-40% cover 280 km^2 (3%) of the area. Concentrations of <20% bulk carbonate do not occur in BZ.

Carbonate sand concentrations range from 25% to 94% and have a mean of 88% (Table 5.2). High carbonate sand concentrations of >60% dominate the seabed in BZ, covering 690 km^2 (7%) (Fig. 8.38; Appendix G). Although these concentrations dominate in BZ, the area of carbonate sand with concentrations >60% is relatively low compared to the other planning zones and covers the smallest area (Appendix H). Carbonate sand concentrations of <20% are not present in BZ.

Carbonate mud concentrations range from 26% to 91% and have a mean of 72% (Table 5.2). Carbonate mud concentrations of >60% cover 410 km^2 (4%) of the total area (Fig. 8.38; Appendix G). The percentage area of >60% carbonate mud in BZ is relatively low compared to the other planning zones and covers the smallest area (Appendix I). Carbonate mud concentrations of <20% cover 1 km^2 (<1%) of the total area.

Geomorphology:— The seabed geomorphology in BZ's is dominated by seven feature types namely: slope, trench/trough, terrace, canyon, shelf, reef and deep/hole/valley (Appendix J). Together these features cover an area of 9,895 km^2 (Table 8.27).

Slope features make up the greatest proportion of seabed environments in BZ, covering more than 50% of the total area, at 5,810 km^2 (59%) (Table 8.27). Slope features cover an area that is 1.8 times greater than the second most abundant feature, trench/troughs. Slope features cover the greatest percentage area out of all seven planning zones. Slope features number 12, which is the fourth highest of all the planning zones.

Table 8.27. Area of geomorphic features occurring within the Buffer Zones (BZ).

Geomorphic Features	**Kilometre^2*	*Percent*	*Count*
Slope	5,810	59	12
Trench/Trough	3,220	33	5
Terrace	450	5	2
Canyon	250	3	4
Shelf	150	1	21
Reef	10	<1	55
Deep/Hole/Valley	<5	<1	1
Total:	9,895	100	100

*Rounded to the nearest 10 km^2.

Trench/troughs cover an area of 3,220 km^2 (33%) (Table 8.27). Trench/troughs are the second most abundant feature, covering an area that is 7 times greater than the area occupied by terrace features. Trench/troughs cover the greatest percentage area out of all seven planning zones. Trench/troughs number 5 individual features, which is the second highest of all the planning zones.

Terrace features cover an area of 450 km^2 (5%) (Table 8.27). Terraces are the third most abundant features and cover an area that is 3 times greater than the area occupied by shelf features and 50 times greater than the area occupied by reefs in this zone. Compared to other planning zones, terraces cover the second greatest percentage area.

Terraces number 2 individual features, a number that is shared with CRZ and is the lowest out of the planning zones.

Canyons cover an area of 250 km^2 (3%) in BZ (Table 8.27). Canyons cover an area that is 1.6 times greater than that covered by shelf features, and 94 times greater than the total kilometre area covered by deep/hole/valleys. Canyons cover the greatest area out of the seven planning zones. Canyons number 4 individual features, which is the lowest of the four zones that contain canyons (Table 8.27).

Shelf features cover an area of 150 km^2 (1%) (Table 8.27). Shelf environments cover an area that is 16 times greater than the area covered by reefs. These features cover the lowest percentage area out of all seven planning zones. Shelf features number 21, which is the second lowest number in all of the planning zone types.

Reef and deep/hole/valley features together cover less than 1% of the total area of the BZ (Table 8.27). These environments occupy the smallest percentage compared with the other six planning zones.

8.9.5. Habitat Protection Zone (HPZ)

HPZ's occur across the Marine Park and are located on the inner, middle and outer shelf, and continental slope, with the majority of HPZ occurring between 40 and 90 m water depth on the middle and outer shelves. The inner shelf contains numerous small sized (<3 km^2) zones, which increase in size on the outer shelf and continental slope (>5,000 km^2). These zones contain a range of seabed environments from nearshore (e.g. Princess Charlotte Bay, Edgecumbe Bay), shallow water (e.g. Magnetic Island), shallow tidal (e.g. Broad Sound) and reef (e.g. Swain Reefs) (Fig 1.1; Appendix J). Shelf edge and deep water (>100 m) continental slope environments are also represented by HPZ.

Sediments:— Seabed sediments in HPZ are characterised by low overall gravel and mud concentrations, and high sand, bulk carbonate and carbonate sand concentrations (Fig. 8.39). Gravel concentrations range from 0% to 97% and have a mean of 16% (Table 5.1). Low gravel concentrations of <20% cover 44,060 km^2 (51%) of the total area of HPZ (Fig. 8.39; Appendix G). Covering 51% of the total area, gravel concentrations of <20% cover the fifth highest percentage area compared to the other planning zone types. Gravel concentrations of >80% cover 650 km^2 (<1%) of the total area (Fig. 8.39).

Sand concentrations range from 2% to 99% and have a mean of 62% (Table 5.1). High sand concentrations of >60% dominate the seabed in HPZ and cover 34,080 km^2 (40%) of the total area (Fig. 8.39). Covering 40% of the total area, concentrations of >60% sand cover the fifth largest percentage area compared to the other planning zone types. Low sand concentrations of <40% cover 8,700 km^2 (11%) (Fig. 8.39), which is the third highest percentage area compared to the other planning zones.

Mud concentrations range from 0% to 98% and have a mean of 22% (Table 5.1). Low mud concentrations of <40% dominate the seabed in HPZ and cover 48,320 km^2 (56%) of the total area (Fig. 8.39; Appendix G). Mud concentrations of >80% cover only 1% or 970 km^2 of the total area of HPZ (Fig. 8.39). Compared to the other planning zones, the percentage area of >80% mud is one of the lowest (Appendix H).

Bulk carbonate concentrations range from 0% to 99% and have a mean of 76% (Table 5.2). Bulk carbonate concentrations of >60% dominate the seabed in HPZ, covering 49,170 km^2 (57%) of the total area (Fig. 8.39; Appendix G). Covering 57% of the total area, the area covered by bulk carbonate concentrations of >60% is the second highest of all the planning zone types (Appendix H). Bulk carbonate concentrations of <20% cover an area of 960 km² (1%) of the total area (Fig. 8.39). At 1%, the percentage area of <20% bulk carbonate is one of the lowest of all the planning zones.

Carbonate sand concentrations range from 2% to 100% and have a mean of 81% (Table 5.2). Carbonate sand concentrations of >80% dominate the seabed in HPZ and cover 37,500 km² (44%) of the total area (Fig. 8.39; Appendix G). Covering 44% of the total area, concentrations of >80% carbonate sand cover the largest percentage area compared to the other planning zone types (Appendix H). Carbonate sand concentrations of <20% cover an area of 520 km² (<1%).
Carbonate mud concentrations range from 0% to 95% and have a mean of 65% (Table 5.2). Carbonate mud concentrations of >60% dominate the seabed in HPZ and cover 30,770 km² (36%) of the total area (Fig. 8.39; Appendix G). Covering 36% of the total area, concentrations of >60% carbonate mud cover the greatest percentage area, out of the seven planning zone types (Appendix H). Carbonate mud concentrations of <20% cover 1,950 km² (2%) of the total area of HPZ (Fig. 8.39). Covering 2% of the total area, the area of <20% carbonate mud covers the lowest percentage area of all seven planning zone types.

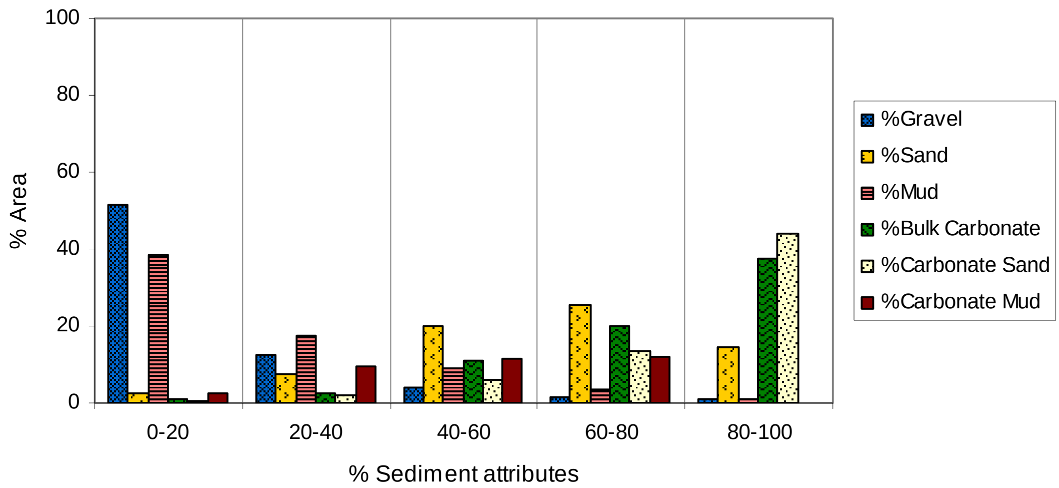

Figure 8.39. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Habitat Protection Zones.

Geomorphology:— The seabed geomorphology is characterised by 14 feature types, namely: shelf, slope, plateau, reef, trench/trough, deep/hole/valley, basin, bank/shoals, terrace, canyon, saddle, pinnacle, tidal-sandwave/sand-bank and apron/fan (Appendix J). Together these features cover an area of 97,225 km² (Table 8.28).

Shelf features are the most extensive in HPZ; covering 31,780 km² (33%), they make up the greatest proportion of seabed environments (Table 8.28). Shelf features cover an area that is 1.3 times greater than the area occupied by the second most extensive feature, slope. Shelf features number 535, which is the highest of the seven zones.

Slope features cover an area of 22,920 km² (24%) in the HPZ (Table 8.28). Slope features are the second most extensive and cover an area that is 1.4 times greater than the area occupied by plateau features. Slope features number 26, which is the second highest of the seven different planning zone types.

Plateaus cover an area of 15,840 km² (16%) in the HPZ (Table 8.28). Plateaus are the third most extensive and cover an area that is 3.6 times greater than the area occupied by trench/troughs. Plateaus cover the greatest percentage area out of all the planning zones and number 74, which is the highest of all the planning zones.

Reefs cover an area of 11,620 km² (12%) in the HPZ (Table 8.28). Reefs are the fourth most extensive and cover an area that is 2.6 times greater than the area occupied by trench/troughs. Reefs cover the third greatest percentage area out of all seven zones. Reefs number 1,741, which is the highest of all the planning zones.

Table 8.28. Area of geomorphic features occurring within the Habitat Protection Zones (HPZ).

Geomorphic Features	**Kilometre²*	*Percent*	*Count*
Shelf	31,780	33	535
Slope	22,920	24	26
Plateau	15,840	16	74
Reef	11,620	12	1741
Trench/Trough	4,380	5	6
Deep/Hole/Valley	3,530	4	57
Basin	3,150	3	19
Bank/Shoals	1,330	1	97
Terrace	1,060	1	23
Canyon	900	1	29
Saddle	610	1	12
Pinnacle	80	<1	6
Tidal-sandwave/Sand-bank	20	<1	8
Apron/fan	<5	<1	1
Total:	97,225	100	2,634

*Rounded to the nearest 10 km².

Individually, the trench/trough, deep/hole/valley, basin, banks/shoals, terrace, canyon, saddle, pinnacle, tidal-sandwave/sand-bank and apron/fan features cover less than 5% of the total area of the HPZ (Table 8.28). At 4%, deep/hole/valley features cover one of the greatest areas as a percentage of the seven planning zone types. Out of the seven planning zones, basins in HPZ cover the second largest percentage area at 3.2%. Terraces cover the second lowest percentage area out of the seven planning zones, at 1%. Canyons cover the second largest percentage area of all the planning zones, at 1%. Saddles cover 1% of HPZ. Pinnacles cover the greatest percentage area in HPZ, at <1%. Compared to the other seven planning zones, tidal-sandwave/sand-bank features cover the lowest percentage area in HPZ, at <1%. Apron/fans cover a percentage area of less than 1% in HPZ, which is the lowest of all the planning zones.

8.9.6. Marine National Park Zone (MNPZ)

MNPZ's occur across the Marine Park on the inner, middle and outer shelf, and continental slope, with the majority of HPZ occurring between 40 and 90 m water depth on the middle and outer shelves. The inner shelf contains numerous small sized (<3 km²) zones, which increase in size on the outer shelf and continental slope (>5,000 km²). These zones contain a range of seabed environments from nearshore (e.g. Princess Charlotte Bay, Edgecumbe Bay), shallow water (e.g. Magnetic Island), shallow tidal (e.g. Broad

Sound) and reefs (e.g. Swain Reefs) (Fig. 1.1; Appendix J). Shelf edge and deep water (>100 m) continental slope environments are also represented in the MNPZ.

Sediments:— Seabed sediments in MNPZ are characterised by low gravel and mud concentrations, high sand concentrations and high bulk carbonate, carbonate sand and carbonate mud concentrations (Fig. 8.40). Gravel concentrations range from 0% to 97% and have a mean of 14% (Table 5.1). Low gravel concentrations of <20% dominate the seabed in HPZ and cover 45,330 km^2 (42%) of the total area (Fig. 8.40; Appendix G). Covering 42% of the total area, the area of <20% gravel is the second lowest of all the planning zones (Appendix H). Gravel concentrations of >80% cover 1,040 km^2 (1%) of the total area of MNPZ. Although the area of >80% gravel is 1%, it has the second highest coverage of the seven planning zones (Appendix H).

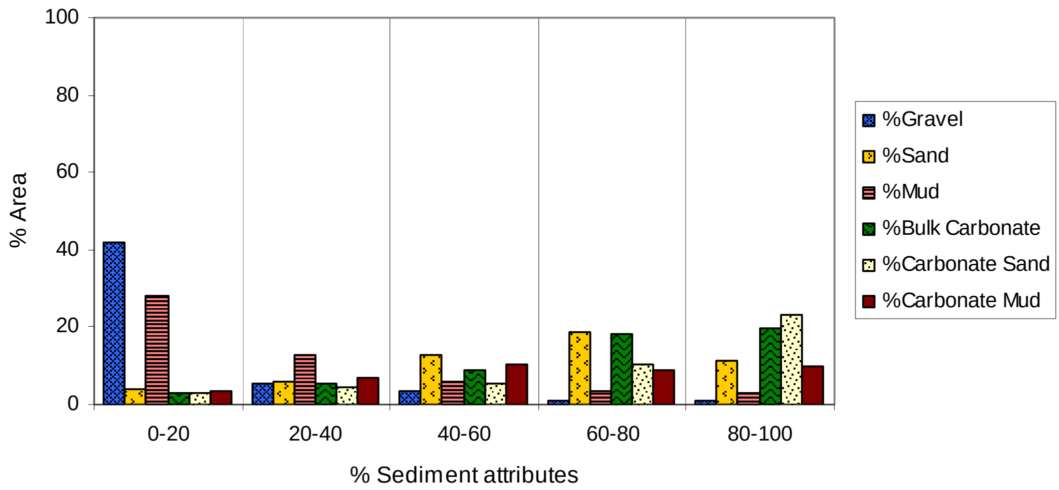

Figure 8.40. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in Marine National Park Zones.

Sand concentrations range from 0% to 100% and have a mean of 60% (Table 5.1). High sand concentrations of >60% dominate the seabed in MNPZ and cover 32,650 km^2 (30%) of the total area (Fig. 8.40; Appendix G). Covering 30% of the total area, concentrations of >60% sand cover the second lowest percentage area of all the planning zone types (Appendix H). Low sand concentrations of <20% cover 4,490 km^2 (4%) of the total area (Fig. 8.40). At 4%, the area of <20% sand is the second highest of the seven planning zones.

Mud concentrations range from 0% to 100% and have a mean of 25% (Table 5.1). Low mud concentrations of <40% dominate the seabed in MNPZ and cover 44,510 km^2 (41%) (Fig. 8.40; Appendix G). Covering 41% of the total area, concentrations of <40% mud cover the second lowest percentage area of the different planning zone types (Appendix H). High mud concentrations of >80% cover an area of 2,940 km^2 (3%) of the total area (Fig. 8.40). At 3%, the area of >80% mud in MNPZ is the second highest of the planning zones.

Bulk carbonate concentrations range from 0% to 100% and have a mean of 67% (Table 5.2). High bulk carbonate concentrations of >60% dominate the seabed in MNPZ and cover 41,090 km^2 (40%) of the total area (Fig. 8.40; Appendix G). Covering 40% of the total area, concentrations of >60% bulk carbonate cover the lowest percentage area of all the different planning zone types (Appendix I). Bulk carbonate concentrations of <20% cover an area of 3,260 km² (3%) (Fig. 8.40). Covering 3% of the total area, concentrations of <20% bulk carbonate cover the third highest percentage area of out of the seven planning zone types.

Carbonate sand concentrations range from 1% to 98% and have a mean of 70% (Table 5.2). High carbonate sand concentrations of >60% dominate the seabed in MNPZ and cover 35,910 km² (33%) (Fig. 8.40; Appendix G). At 33%, the area of >60% carbonate sand in MNPZ is the second lowest out of the seven planning zones (Appendix I). Low carbonate sand concentrations of <20% cover 3,390 km² (3%) of the total area (Fig. 8.40). Covering 3% of the total area, concentrations of <20% carbonate sand cover the third highest percentage area out of the seven planning zone types.

Carbonate mud concentrations range from 0% to 95% and have a mean of 57% (Table 5.2). Carbonate mud concentrations of 40-60% dominate the seabed in MNPZ, covering 11,040 km² (10%) of the total area (Fig. 8.40; Appendix G). Covering 10% of the total area, concentrations of 40-60% cover the greatest percentage area compared to the other seven planning zone types (Appendix H). Carbonate mud concentrations of >80% cover 10,500 km² (10%) of the total area.

Geomorphology:— The seabed geomorphology is dominated by 17 features types, namely: shelf, slope, plateau, trench/trough, reef, deep/hole/valley, terrace, basin, saddle, canyon, bank/shoals, continental-rise, tidal-sandwave/sand-bank, ridge, pinnacle, knoll/abyssal-hills/hills/mountain/peak and apron/fan (Appendix J). MNPZ's contain the most diverse seabed environments out of all seven planning zones. Together these geomorphic features cover an area of 114,460 km² (Table 8.29).

Shelf features cover 37,320 km² (33%) of the total area of MNPZ (Table 8.29). Shelf features are the most extensive feature in MNPZ and cover an area that is 6 times greater than the area occupied by reef features in this zone. Shelf features number 243, which is the second highest of all the planning zones.

Slope features cover an area of 32,630 km² (29%) in the MNPZ (Table 8.29). Slope features are the second most extensive and cover an area that is 1.8 times greater than the area occupied by plateaus in this zone and cover the second highest percentage area out of all the planning zones. Slope features number 53, which is the highest number of this feature that occurs in any of the seven planning zones.

Plateaus cover 18,000 km² (16%) of the total area of MNPZ (Table 8.29). Plateaus cover an area that is 2.7 times greater than the area occupied by the next most abundant feature in this zone, trench/troughs and cover the second highest percentage area out of the seven planning zones. Plateaus number 35, which is the second highest of all the planning zones.

Trench/troughs cover 6,660 km² (6%) of the total area of MNPZ (Table 8.29). Trench/troughs are the fourth most extensive feature and cover an area that is 8 times greater than the area occupied by other depressions; canyons, which are the tenth most extensive feature. Trench/troughs cover the second highest percentage area out of the seven planning zones. Trench/troughs number 6, which shares the equal highest with HPZ, compared to the other planning zones.

Reefs cover 6,130 km² (5%) of the total area of MNPZ (Table 8.29). Reefs are the fifth most extensive feature and cover an area that is 11.5 times greater than the area occupied by other protruding structures; bank/shoals, which are the eleventh most extensive feature. Reefs cover the third lowest percentage area out of the seven planning zones. Reefs number 892, which is the second highest number of the seven planning zone types.

Individually, deep/hole/valley, terrace, basin, saddle, canyon, bank/shoals, continental-rise, tidal-sandwave/sand-bank, ridge, pinnacle, knoll/abyssal-hills/hills/mountain/peak and apron/fan features occupy less than 5% of the total area of the MNPZ's (Table 8.29). Deep/hole/valleys cover the greatest area of 4% or 4,510 km², compared to the other planning zones. Continental-rises, ridges and knoll/abyssal-hills/hills/mountain/peaks are unique to this zone and cover 420 km² (<1%), 70 km² (<1%) and 50 km² (<1%) of the total area, respectively. Pinnacles cover less than 1% of the total area, at 49 km². The MNPZ is one of two planning zones that contain apron/fans, which cover the greatest area in these zones, at 45 km² (<1%), compared with all the other planning zones.

Table 8.29. Area of geomorphic features occurring within the Marine National Park Zones (MNPZ).

Geomorphic Features	**Kilometre^2*	*Percent*	*Count*
Shelf	37,320	33	243
Slope	32,630	29	53
Plateau	18,000	16	35
Trench/Trough	6,660	6	6
Reef	6,130	5	892
Deep/Hole/Valley	4,510	4	41
Terrace	4,290	4	26
Basin	1,940	2	16
Saddle	860	1	8
Canyon	810	1	23
Bank/Shoals	530	<1	91
Continental-rise	420	<1	1
Tidal-sandwave/Sand-bank	140	<1	1
Ridge	70	<1	1
Pinnacle	50	<1	3
Knoll/Abyssal-hills/Hills/Mountain/Peak	50	<1	2
Apron/fan	50	<1	1
Totals:	114,460	100	1,443

*Rounded to the nearest 10 km^2.

8.9.7. General Use Zone (GUZ)

GUZ's are found across the Marine Park, and principally occur on the inner, middle and outer continental shelf, and to a lesser extent on the continental slope. GUZ generally comprise large zones covering extensive areas (<37,000 km²), such as offshore Gladstone. Zones of less than 1,000 km² are rare; the smallest GUZ covers 12.5 km² in Edgecumbe Bay near Bowen (Fig. 1.1; Appendix J). These zones encompass a range of benthic environments from shallow water (<20 m), coastal and nearshore regions (e.g. Keppel Bay), strong tidal regions (e.g. Broad Sound), inter-reefal areas (e.g. Hydrographers Passage; Swain Reefs) and out to deep waters (>200 m) on the slope (e.g. Coral Sea, east of Mackay; Capricorn Channel) (Fig. 1.1; Appendix J).

Sediments:— Seabed sediments in GUZ are characterised by low overall gravel and mud contents, and high sand, bulk carbonate, carbonate sand and carbonate mud concentrations (Fig. 8.41). Gravel concentrations range from a minimum of 0% to 90%

and have a mean of 8% (Table 5.1). Low gravel contents of <20% dominate the seabed in GUZ and cover 100,440 km² (87%) of the total area (Fig. 8.41; Appendix G). At 87%, concentrations of <20% gravel cover the greatest area compared with the other planning zones (Appendix H). High gravel concentrations of >80% cover a much smaller area of 140 km² (<1%) (Fig. 8.41).

Sand concentrations range from 0% to 100%, with a mean of 65.6% (Table 5.1). Concentrations of >60% cover an area of 70,000 km² (60%) of the total area (Fig. 8.41; Appendix G). Covering 60% of the total area, concentrations of >60% sand cover the greatest area out of all the seven planning zone types (Appendix H). Low sand concentrations of <20% cover 2,340 km² (2%) of the total area of GUZ's (Fig. 8.41).

Mud concentrations range from 0% to 95% and have a mean of 25% (Table 5.1). Low mud concentrations of <20% dominate the seabed in GUZ and cover 53,350 km² (46%) of the total area (Fig. 8.41; Appendix G). Covering 46% of the total area, concentrations of <20% mud cover the third highest area out of all seven planning zone types (Appendix H). High mud concentrations of >80% cover 1,430 km² (1%) of the total area of GUZ (Fig. 8.41). Out of the seven planning zones, mud concentrations of >80% cover the second lowest area, at 1%.

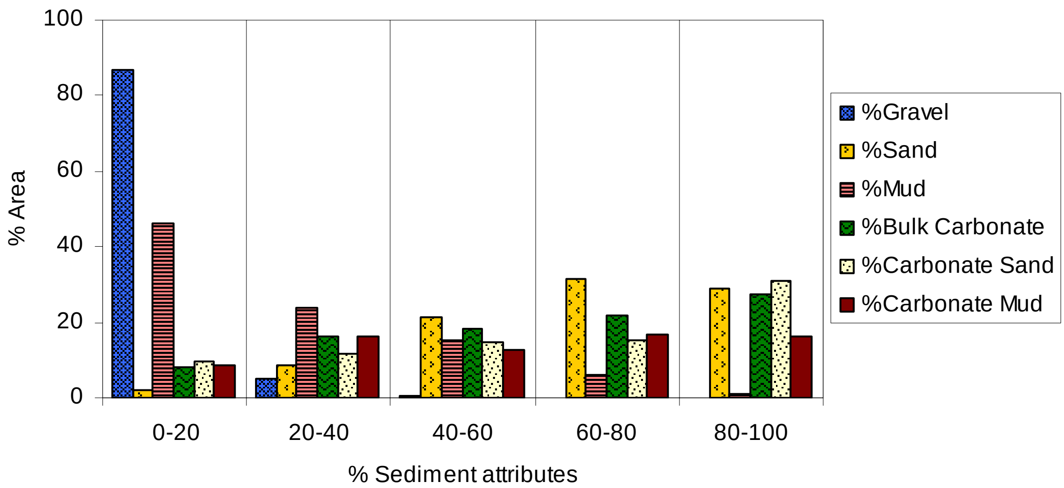

Figure 8.41. Histograms of the percentage area covered by %Gravel, %Sand, %Mud, %Bulk Carbonate, %Carbonate Sand and %Carbonate Mud concentrations in General Use Zones.

Bulk carbonate concentrations range from 0% to 99% and have a mean of 59% (Table 5.2). High bulk carbonate concentrations of >60% dominate the seabed, covering 56,730 km² (49%) of the total area (Fig. 8.41; Appendix G). Covering 49% of the total area, concentrations of >60% bulk carbonate cover the third highest area out of all the planning zone types (Appendix H). Low bulk carbonate concentrations of <20% cover 9,500 km² (8%) of the total area of GUZ (Fig. 8.41). The percentage area covered by <20% bulk carbonate is the second highest compared with the other planning zone types.

Carbonate sand concentrations range from 1% to 100% and have a mean of 61% (Table 5.2). High carbonate sand concentrations of >60% dominate the seabed in these zones and cover 53,630 km² (46%) of the total area of GUZ (Fig. 8.41; Appendix G). At 46%, carbonate sand concentrations of >60% cover the fourth highest area out of the seven planning zones (Appendix H). Low carbonate sand concentrations of <20% cover an area of 11,040 km² (10%) of GUZ (Fig. 8.41), and covers the second highest area compared with concentrations in the other six planning zones.

Carbonate mud concentrations range from 0% to 95% and have a mean of 54% (Table 5.2). High carbonate mud concentrations of >60% dominate the seabed in the GUZ and cover 38,480 km² (33%) of the total area (Fig. 8.41; Appendix G). The area of >60% carbonate mud covers the second highest percentage area compared with other planning zones (Appendix H). Low carbonate mud concentrations of <20% cover an area of 10,280 km² (9%) of the total area (Fig. 8.41). The percentage area of <20% carbonate mud covers the second highest area compared to the other planning zones.

Geomorphology:— The seabed geomorphology contains 14 geomorphic feature types, including: shelf, slope, plateau, terrace and basin features, which each cover more than 5% of the total area (Appendix J). Features that each cover less than 5% of the total area are: saddle, deep/hole/valley, bank/shoals, reef, tidal-sandwave/sand-bank, canyon, trench/trough, pinnacle and knoll/abyssal-hills/hills/mountain/peak features. GUZ contain a relatively large range of geomorphic features and have the second most diverse seabed environments. Together, geomorphic features in GUZ cover an area of 116,520 km² (Table 8.30).

Shelf features dominate GUZ, and cover an area of 64,530 km² (55%) in the GUZ (Table 8.30). At 64,530 km² shelf features cover an area that is 3.8 times greater than the area occupied by the next most extensive features, slope features. Shelf features cover the third highest area out of all 7 planning zones. Shelf features number 42, which is the fourth highest amount compared to the other planning zones.

Slope features also form a significant proportion of seabed areas the GUZ and cover 16,880 km² (14%) of the total area (Table 8.30). Slope features are the second most extensive feature and cover an area that is 1.6 times greater than the area occupied by plateaus. Slope features cover an area that is the fourth highest in comparison to the other planning zones. Slope features number 13, which is the third highest of all the planning zones.

Plateaus cover an area of 10,310 km² (9%) in the GUZ (Table 8.30). Plateaus are the third most extensive feature and cover an area that is 1.2 times greater than the area occupied by the fourth most extensive feature, terraces. Plateaus cover the lowest percentage area compared to the other planning zones. Plateaus number 26, which is the third highest of all the planning zones.

Terraces cover an area of 8,040 km² (7%) in the GUZ (Table 8.30). Terraces are the fourth most extensive feature in GUZ and cover an area that is twenty one times greater than the area occupied by the tenth most extensive feature, tidal-sandwave/sand-banks. Terraces cover the greatest percentage area compared to the other planning zones. Terraces number 6, which is the third highest of all the planning zones.

Basins cover an area of 5,840 km² (5%) in the GUZ (Table 8.30). Basins are the fifth most extensive feature and cover an area that is 19.5 times greater than the area occupied by trench/troughs. Basins cover the greatest percentage area when compared to the other planning zones. Basins number 5, which is equally the lowest with CRZ of all the planning zones.

Individually, saddle, deep/hole/valley, bank/shoals, reef, tidal-sandwave/ sand-bank, canyon, trench/trough, pinnacle and knoll/abyssal-hills/hills/mountain/peak features all occupy less than 5% of the total area of GUZ (Table 8.30). Saddles and tidal-sandwave/sand-banks cover the highest percentage area out of all the planning zones, of 4.4% and <1% respectively. Reefs cover less than 1% of the total area of GUZ, which is the second lowest area compared to the other planning zones. Canyons and trench/troughs cover the lowest percentage area of <1%, which is lower than the other planning zones. Pinnacles cover less than 1% of the area in GUZ and cover the lowest area, along with MNPZ. Knoll/abyssal-hills/hills/mountain/peaks cover 25 km^2 (0.02%) in GUZ, which is lower than the other planning zones.

Table 8.30. Area of geomorphic features occurring within the General Use Zones.

Geomorphic Features	*Kilometre^2*	*Percent*	*Count*
Shelf	64,530	55	42
Slope	16,880	14	13
Plateau	10,310	9	26
Terrace	8,040	7	6
Basin	5,840	5	5
Saddle	5,160	4	4
Deep/Hole/Valley	3,280	3	24
Bank/Shoals	830	1	73
Reef	610	1	180
Tidal-sandwave/Sand-bank	380	<1	5
Canyon	300	<1	8
Trench/Trough	300	<1	4
Pinnacle	40	<1	8
Knoll/Abyssal-hills/Hills/Mountain/Peak	20	<1	1
Total:	116,520	100	399

Rounded to the nearest 10 km^2.

8.10. Appendix J - Planning zone maps

Maps of the geomorphology and sediment attributes of the planning zones are shown for each of the Management Areas, and are provided on the data CD-ROM.

8.11. Appendix K - Poster size (A0) maps

Maps of the regional sediment distribution across the Marine Park, for the six sediment attributes are provided on the data CD-ROM.