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A Carbonate and Terrigenous Sediment Budget for Inshore Turbid Reefs on the Great Barrier Reef

Thesis submitted by

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Abstract

Inshore turbid zone coral reefs on the central Great Barrier Reef (GBR) are situated within 20 km of the coast where terrigenous sediments influence coral communities, carbonate production and reef growth. They exist within a range of geomorphic settings from open coastal settings to muddy coastal embayments, and include fringing and nearshore reefs and shoals. Inshore regions on the central GBR are characterised by high sediment yields and suspended sediment loads, elevated nutrients and fluctuating salinities. These marginal environmental conditions are widely viewed as unfavourable for sustained and vigorous coral reef growth, and thus it is commonly claimed that inshore turbid reefs are stressed and/or degraded. However, recent research has challenged this and demonstrates that many have high coral cover and robust coral communities, and that reefs have rapidly accreted to sea level despite exposure to elevated terrigenous sediments. The importance of terrigenous sediments for coral community composition and turbid zone reef growth has yet to be quantitatively evaluated due to a lack of detailed data and limited knowledge on sedimentary interactions and processes in these highly dynamic sedimentary settings.

The overall aim of this research was to provide a comprehensive assessment of carbonate and terrigenous sediment regimes for inshore turbid reefs on the central GBR by quantifying carbonate production and destruction together with sediment deposition, resuspension and transport across the reef. Specifically, the objectives of this research were to: 1) examine benthic community composition and distribution; 2) examine spatial variations in sediment texture and composition; 3) investigate the influence of spatial and temporal variations in turbidity on benthic cover; 4) quantify the sedimentary regime and examine its role in reef growth; 5) investigate spatial and temporal variations in coral growth and carbonate production; and 6) quantify carbonate production and destruction together with sediment import, storage and export to assess reef growth. This research focused on two inshore turbid zone reefs on the central GBR; Middle Reef, a nearshore reef situated between Magnetic Island and Townsville, a large urban area with a major port; and Paluma Shoals, approximately 30 km north of Townsville on a more exposed coastline and distal to direct anthropogenic pressures that may influence Middle Reef. These two sites were chosen to examine the influence of variable hydrodynamic and sedimentary regimes on coral community composition and distribution, and on net carbonate production and reef growth.

At both reefs coral cover was high (>30%) and diversity was moderate to high (>50 species). The coral community distribution was independent of depth and was instead driven by spatial variations in sedimentation rates and turbidity, largely controlled by reef morphological interactions with waves, currents and tides. Coral communities were dominated by either fast-growing species such as *Acropora* and *Montipora*, most abundant on the exposed windward reef edges, sediment tolerant species such as *Turbinaria*, *Galaxea* and *Goniopora* which dominated the leeward reef edges and were also abundant at the base of windward reef slopes, and *Goniastrea* which dominated the reef flats. Investigations into temporal community dynamics at Middle Reef show that coral cover on the windward reef edge (73%) has increased over the last 15 years despite a history of episodic mortality events. These data demonstrate that these coral communities are robust and resilient, and challenge perceptions that inshore turbid reefs are degraded.

Reef morphology influenced sediment composition, distribution and resuspension over both reefs. Sediments consisted of varying proportions of silt, sand and gravel, and the carbonate component was dominated by coral and mollusc fragments. The mean grain size decreased from the eastern windward reef slopes to the western sheltered leeward edge reflecting wave energy dissipation across both reefs. The mean grain size was greater at Paluma Shoals, where higher wave energy resuspended and redistributed sediments over the reef and finer sediments were winnowed away. As such, sediment composition and distribution was not significantly correlated to reef benthos. In contrast, lower wave energy and limited redistribution of sediments at Middle Reef resulted in a strong correlation between sediment composition and reef benthos. Given spatial distributions in both wave energy and sediment composition, sediment resuspension rates and turbidity also varied across both reefs. These turbidity gradients were reflected in coral community distributions with a greater abundance of heterotrophic corals in reef habitats characterised by rapid and large fluctuations in turbidity. Local wind speed data accounted for <73% and <56% in the variance in turbidity at Paluma Shoals and Middle Reef respectively, and was used to generate a site-specific turbidity model. The model will enable future researchers to direct real-

time management for turbidity risk assessments, identify increases in turbidity above the natural turbidity regime and assess the implications for coral communities and reef health.

A detailed quantitative assessment of the sediment regime (deposition, resuspension and removal) developed using both established and new techniques, reveals that despite high sediment flux rates (<20, 000 tonnes annually), net sedimentation rates are low (<50 $g/m^2/day$) due to sediment resuspension and removal. Established techniques included the use of data loggers to measure spatial and temporal variations in turbidity with waves and currents, whereas sedimentation and resuspension rates were measured using 'sediment trays'. The use of sediment trays overcame the limitations of commonly used 'sediment traps' which over-estimate sedimentation rates and preferentially collect larger particles. The sediment regime was quantified across two depth zones (0.5 to -1.5 m, <-1.5 to -3.5 m at LAT), and within five geomorphic habitats (eastern, central and western windward reef edge, inner basins or reef flat and leeward reef edge) to provide data for a model that illustrated the direction and rate of sediment delivery, deposition and removal across both reefs. The model illustrated that >81% of sediments imported annually onto turbid reefs are exported as suspended sediments due to high wave energies, which corresponded to elevated turbidity (>50 mg/L). These results suggest that despite a high sediment flux rate through these reef systems, sediment deposition is limited and therefore does not impede inshore reef growth and survival within terrigenous settings.

Coral growth is influenced by environmental conditions such as sea surface temperatures (SST) and water quality, and can be used to assess coral condition as well as the rate of carbonate production. In this study the coral growth rates (linear extension, density, calcification rates) of three fast-growing corals (*Acropora, Montipora, Turbinaria*), common to both inshore turbid reef and offshore clear-water reefs, were studied *in situ* on Middle Reef to provide some of the first data used to quantify carbonate production for inshore turbid reefs. Our investigations found that *Acropora* growth rates (average rate of 6.3 cm/year) were comparable to those measured at similar depths on mid to offshore reefs on the GBR. *Montipora* linear extension (2.9 cm/year) was greater than current estimates available for both turbid and clear-water reefs, and *Turbinaria*, although characterised by low linear extension (1 cm/year), had a dense skeleton (1.3 g/cm^3) and may be more resilient to physical damage. Spatial variations in coral growth and carbonate production rates were driven by water motion and sediment dynamics, and temporal variations indicated that coral growth was lower during the summer when SSTs (mean 29 ^oC) and rainfall (monthly 500 mm) were high. In summary, high contemporary growth rates on inshore turbid reefs is in accord with rapid accretion rates established from the fossil record for numerous turbid reefs on the GBR and indicate that corals on Middle Reef are resilient to their marginal environmental conditions.

This research provides the first quantitative assessment of carbonate production and destruction together with sediment import, storage and export, to evaluate the rate and mode of reef growth for inshore turbid reefs. The mean net carbonate production rate was 12 kg/m^2/year at Middle Reef and 7 kg/m^2/year at Paluma Shoals, although varied between habitats with lowest rates measured on shallow reef flats (>1 kg/m^2/year) and highest rates at the base of reef slopes (<19 kg/m^2/year). The mean net carbonate production rate was converted to a reef accretion rate, which was greater at Middle Reef (5.2 mm/year) reflecting the higher coral and *Acropora* cover than at Paluma Shoals (3 mm/year). The mode of reef growth for each reef habitat was determined by comparing the rate of sediment deposition to carbonate accumulation; if carbonate production was high and sediment deposition limited, it was production-dominated; if sediment accumulation was greater than carbonate production, it was import dominated; and if the rate of sediment resuspension was greater than the rate of sediment deposition, it was export dominated. The mode and rate of reef growth were used to construct a reef growth model, with accretion in deep reef habitats taken as a proxy for early reef growth. The model provides an assessment of reef growth in a terrigenous setting with depth and time, quantitatively links sedimentary processes to ecological processes over time and space, and can be used to assess how reef growth may respond to future environmental changes such as increased sediment delivery, rising sea-level and increased SSTs.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

1.1 Coral reefs

At a global scale coral reef ecosystems are threatened by multiple disturbances that may reduce species and habitat diversity, and can cause reef degradation (Hughes, 1994; Jackson *et al.*, 2001; Pandolfi *et al.*, 2003). Disturbances to coral reefs are either acute or chronic (Connell, 1997). Acute disturbances, such as coral bleaching, have increased in frequency and severity in recent years resulting in significant and rapid reductions in live coral cover at regional scales (Bruno and Selig, 2007; Graham *et al.*, 2008). Reef recovery following acute disturbance events depends on the severity of the event and reef resilience (largely driven by coral cover and diversity). In contrast, chronic threats, such as eutrophication and sediment stress, are slow to change reef ecosystems but exert a continuous pressure which may diminish reef resilience (McCulloch *et al.*, 2003; Fabricius, 2005). Excessive nutrients stimulate macro-algal growth (De'ath and Fabricius, 2010), increase disease prevalence (Bruno *et al.*, 2003), and reduce coral reproduction (Koop *et al.*, 2001), all factors that lead to reduced coral cover and limited reef recovery. Chronic effects of high sediment loads include turbidity which reduces water transparency and limits light availability for phototrophic organisms (Loya, 1976; Anthony and Connolly, 2004), and sediment deposition, which smothers and buries reef benthos (Hubbard, 1986; Fabricius and Wolanski, 2000; Philipp and Fabricius, 2003). While there is some detailed knowledge on how disturbance events influence reef benthic communities in the short-term, less is known of the long-term effects of multiple disturbances on reef ecosystems (Wilson *et al.*, 2006; Hughes *et al.*, 2010).

The Great Barrier Reef (GBR) is the most extensive coral reef ecosystem on earth encompassing 2,900 coral reefs over an area of 345,000 km^2, and consists of a range of habitats and reef types from subtropical to tropical reefs, and across the continental shelf from inshore turbid waters to offshore clear-waters (Hopley *et al.*, 2007). In 1981 the GBR became a world heritage site due to its high habitat and species diversity. The GBR is protected by a zoning system and is generally subjected to low human pressures, but is nonetheless showing evidence of declines in live coral cover (Pandolfi *et al.*, 2003; Bruno and Selig, 2007; Hughes *et al.*, 2011; Sweatman *et al.*, 2011). The extent and severity of declining coral cover is hotly debated; Hughes *et al.* (2011) argue that the GBR is losing reef resilience due to multiple disturbance events and incomplete recoveries, while Sweatman *et al.* (2011) argue that the drop in live coral cover from 28% in 1986 to 22% in 2004, is largely due to localised declines in sub-regions of the GBR rather than general declines in coral cover. However, both agree that some of the sub-regions most affected by both global (e.g. coral bleaching) and local (e.g. increased nutrient input) disturbances are inshore, close to heavily modified coastal catchments where high sedimentation, turbid waters and nutrient inputs are considered to threaten inshore reefs. As such, many inshore reefs on the GBR, termed inshore turbid reefs, are considered more vulnerable than clear-water offshore reefs to reef degradation from global, acute disturbances despite zoning measures and sparse human coastal populations (Wolanski and De'ath, 2005).

1.2 Controls on coral reef growth

Coral reefs are topographically complex three dimensional structures created from the accumulation of calcium carbonate and provide a number of microhabitats for a diverse assemblage of marine benthic flora and fauna (Connell, 1978). The accumulation of calcium carbonate and reef growth is controlled by the balance between carbonate production and destruction. Carbonate producers include corals, calcareous coralline algae (CCA), molluscs, crustaceans, bryozoans, foraminiferans, and segmented worms, however, corals are typically the main carbonate producer and framework builder (Hubbard *et al.*, 1990). A fall in the abundance of carbonate producers, particularly corals, will lead to a reduction in net carbonate production and accumulation, and therefore reef growth and development. Carbonate accumulation rates also decrease if destructive processes increase. Carbonate can be broken down biologically by borers and grazers (e.g. urchins), physically from high wave activity during storm events, and/or chemically (e.g. ocean acidification). The reef fabric is primarily composed of coral clasts but may also accumulate reefal sediments, from biological and physical destructive processes (Hutchings, 1986; Scoffin, 1992), and terrigenous sediments, which can be consolidated into the reef fabric following encrusting and cementation processes that help to stabilise the reef structure (Scoffin, 1992; Perry, 1999; Rasser and Riegl, 2002). The balance between carbonate production and destruction, and sediment production and accumulation will influence the rate and mode of reef growth, and reef stability.

Environmental pre-requisites essential to reef growth in tropical waters include suitable substrate for coral larval settlement; water depths less than 100 m, with optimal reef growth at less than 20 m; temperature range between 18 to 36 ^{0}C, with an optimal range between 26 to 28 ^{0}C; and salinities between 25 to 42 ppt, with an optimal range between 33 to 36 ppt (Coles and Jokiel, 1978; Hubbard, 1997; Kleypas *et al.*, 1999a). On clear-water offshore reefs the fall in light intensity and wave energy with depth are also considered primary environmental controls of community assemblage composition and distribution leading to depth related benthic zones (Hubbard and Scaturo, 1985; Huston 1985; Dennison and Barnes, 1988). However, the attenuation of light with depth is not always systematic and can be confounded by factors such as turbidity. Turbidity increases when deposited sediments are resuspended by waves, and is typically high in shallow inshore waters where sediment deposits are within the wave resuspension zone, and fluvial runoff periodically delivers large volumes of terrigenous sediments, freshwater and nutrients to the coast. Turbidity reduces light transmittance through the water column and in inshore regions of the GBR accounts for >70% of the variation in annual light irradiance at only 1.5 m below the sea surface (Anthony *et al.*, 2004). Limited light availability compresses depth related changes in benthic communities and limits the depth to which corals grow. At depths outside the wave resuspension zone, sediment deposition rates increase and corals are at risk of smothering and burial. Therefore, on inshore turbid reefs, the balance between sediment resuspension and deposition is a dominant control on reef benthos (Done, 1982; Larcombe and Woolfe, 1999a; Browne *et al.*, 2010), and leads to different community composition and distributions than on clear-water offshore reefs, which will ultimately influence the distribution of carbonate productivity and reef growth.

1.3 Inshore turbid reefs

Inshore turbid reefs of the central GBR are situated within 20 km of the Queensland coast where marginal environmental conditions (high sediment loads, excessive nutrients) are used to support claims that these reefs are stressed and/or degraded (Neil *et al.*, 2002; McCulloch *et al.*, 2003; Woolridge *et al.*, 2006). However, many turbid zone reefs have high coral cover (>30 %) and diversity (>100 species; Veron, 1995; DeVantier *et al.*, 2006), are composed of temporally stable coral species as evidenced from palaeoecological reconstructions of reef growth using reef cores (Riegl *et al.*, 1995; McClanahan and Oburu, 1997; Ayling and Ayling, 1999a), are actively and rapidly accreting (Smithers and Larcombe, 2003; Perry and Smithers, 2006), and are able to recover quickly from periodic setbacks such as flood events and cyclones to which they are regularly exposed (Ayling and Ayling, 2005; Browne *et al.*, 2010). Furthermore, reef cores also indicate that many inshore reefs whose growth was regionally slowed around 2000 years ago, well before European settlement, have since entered into an active reef growth phase despite modern sedimentary settings and anthropogenic pressures (Perry and Smithers, 2010; Perry and Smithers, 2011). These data suggest that community assemblages have not changed significantly and modern day sedimentary conditions inshore are comparable to those prior to European settlement (<150 years BP), demonstrating that many inshore reefs are not degraded but potentially resilient reefs having adapted to marginal environmental conditions.

Few scientific studies have been conducted on inshore turbid reefs compared to clear-water offshore reefs, limiting knowledge on the key ecological, geological and physical processes that influence their growth and development. Inshore turbid reefs are likely to be controlled by a combination of physical and ecological processes, including the sedimentary regime and its driving forces (waves, currents, tides), and coral adaptations to sedimentation and turbidity. The importance of sediments to the rate and mode of reef growth is potentially high given the large volumes of terrigenous sediments observed in reef cores (Perry, 1999; Smithers and Larcombe, 2003; Perry, 2005), and also the dominance of sediment tolerant coral species both in historic and modern community assemblages (Anthony and Fabricius, 2000; Sofonia and Anthony, 2008; Palmer *et al.*, 2010). However, collecting data in inshore regions where limited visibility and hazardous marine life occur is difficult, and has lead to a lack of long-term quantitative assessments on the sedimentary regime and its driving forces. A quantitative evaluation of the sedimentary regime is required to provide knowledge on how sediments influence corals, carbonate productivity and reef growth.

1.4 Aims and objectives

The aim of this study was to provide a quantitative assessment of carbonate and terrigenous sediment regimes for inshore turbid reefs on the central GBR. Key differences in the geomorphological and environmental setting between turbid reefs and clear-water reefs are evaluated together with a review of inshore turbid reef growth, community assemblages and reef recovery following disturbance events. The review highlights the lack of studies on inshore turbid reefs and subsequent knowledge gaps on reef ecology and carbonate productivity, and physical processes such as the sedimentary regime. This study aims to address these knowledge gaps by quantifying spatial and temporal variations in carbonate productivity and sedimentary processes (imports, storage, exports) for two inshore turbid reefs on the GBR. Key objectives of this study are:

1. To examine benthic community composition and distribution
2. To examine spatial variations in sediment texture and composition in relation to reef morphology and benthic cover
3. To investigate spatial and temporal variations in turbidity
4. To quantify the sedimentary regime and examine its role in turbid reef growth
5. To investigate spatial and temporal variations in coral growth rates and carbonate production
6. To quantify carbonate production and destruction together with sediment import, storage and export

1.5 Significance of the research

This study provides the first detailed study of carbonate productivity for inshore turbid reefs on the GBR, using a carbonate budget approach, and provides the first quantitative study of sediment dynamics at the intra-reef scale for coral reefs globally. As such, a number of new data sets have been collected. These include:

1. high resolution data on reef morphology and benthic cover for an inshore turbid reef on the GBR

2. detailed assessments on spatial and temporal variability in turbidity within reef habitats for an inshore turbid reef on the GBR
3. field-based assessments of coral growth rates for *Turbinaria* and *Montipora*
4. assessments of all three coral growth parameters (density, linear extension, calcification rates) for fast-growing coral species on inshore turbid reefs on the GBR
5. quantitative assessment of sediment dynamics within reef habitats using a new approach that measures net sedimentation, resuspension and sediment fluxes.
6. quantitative assessments of carbonate budgets for the GBR
7. quantitative assessments of terrigenous sediments for reef growth.

Data on carbonate budgets have been combined with data on sediment dynamics to provide a reef growth model. The model illustrates how the rate and mode of reef growth varies with time and water depth, and provides a new approach to address concerns over reef vulnerability to future environmental change.

1.6 Study location

This research focused on Middle Reef (19^{o}11.70′S, 146^{o}48.70′E) in Cleveland Bay, and Paluma Shoals (19^{0}7.08'S, 146^{0}33.23'E) in Halifax Bay, two inshore turbid reefs off the north Queensland coast (Fig. 1.1). Middle Reef is a nearshore patch reef situated in shallow waters (<4 m at LAT) and surrounded by muddy sands and sandy muds over a muddy Pleistocene clay unit (Carter *et al.*, 1993; Lou and Ridd, 1997). Middle Reef lies approximately 2 km to the south (S) of Magnetic Island and 4 km offshore from Townsville, where it is somewhat sheltered from prevailing winds and waves. However, Middle Reef is potentially exposed to a wide range of human influences and contaminants that may stress reef benthos. Townsville, Australia's most populous

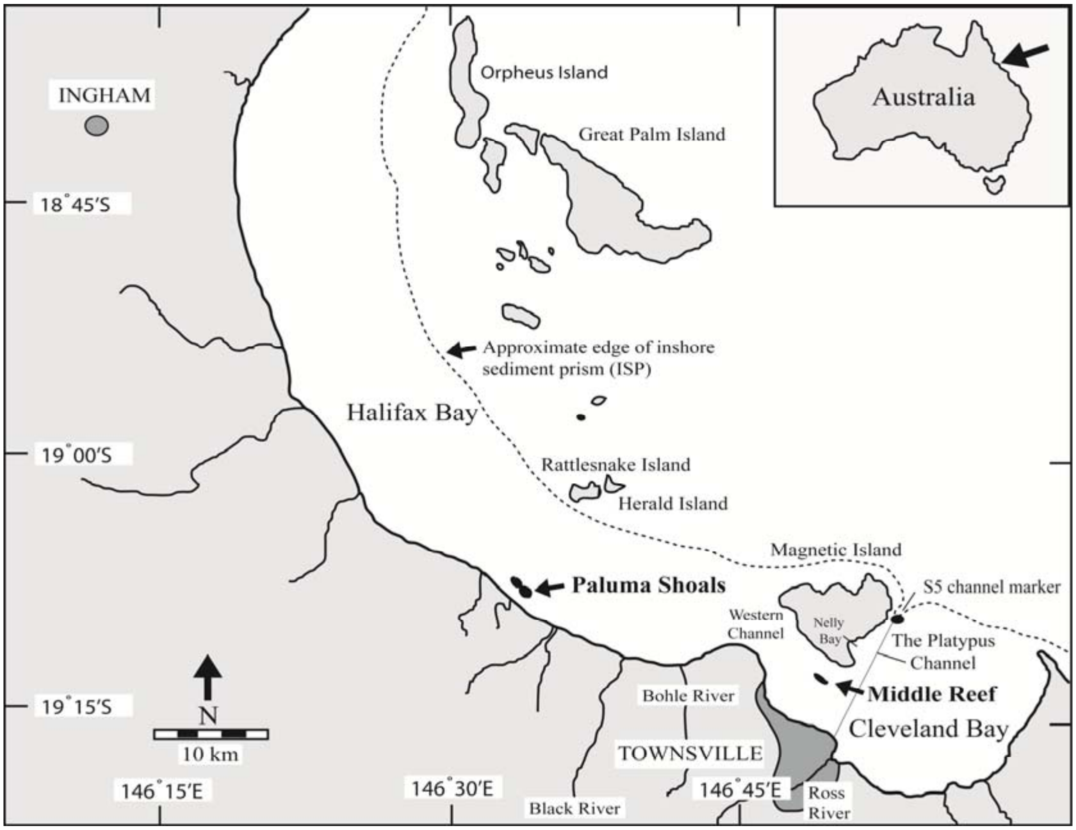

Figure 1.1: Location of Middle Reef and Paluma Shoals on the central Great Barrier Reef.

tropical city (population ~ 185,800 in 2009-2010 census), with a sprawling urban area (215 km^2; 2006 Census of Population and Housing), and a significantly modified catchment, is situated along Cleveland Bay's south-west (SW) edge, and is also home to a large international port accessible to large ships via the Platypus channel which lies approximately 2 km east (E) of Middle Reef. In contrast, Paluma Shoals is situated 30 km to the north (N) of Townsville, where direct anthropogenic influences such as boating activity and contaminants from modified catchments are less severe. Halifax Bay is more exposed to prevailing winds and waves than Cleveland Bay, but Paluma Shoals is also situated in shallow waters (<3 m at LAT) and surrounded by muddy sands and sandy muds.

The tidal regime is semi-diurnal with a maximum range of 3.8 m during the spring tides. Current speeds are stronger during the flood tide and can reach >0.7 m/s during the extreme spring tides (Belperio, 1978). Current and wind-waves transport sediments northwards as a result of the SE trade winds which persist during the winter months (April – November), and NE facing bays, protected from prevailing wind and waves, accumulate sediments (Larcombe *et al.*, 1995). Wind-driven waves are the main agent of sediment resuspension and following 1 - 2 days of high wave activity (>1 m wave height), turbidity can rise to >50 mg/L at Middle Reef (Larcombe *et al.*, 1994) and >100 mg/L at the more exposed Paluma Shoals; conditions estimated to occur for approximately 34% of the year (Larcombe *et al.*, 2001). Turbidity also increases following heavy rainfall during the summer months (>500 mm/month; December to February) as river flood plumes deliver sediments and freshwater into the bays. The Ross River, situated 7 km to the SE of Middle Reef in Cleveland Bay, and the Bohle River and the Black River situated 10 km to the S of Paluma Shoals in Halifax Bay, have a combined annual sediment discharge of 0.13-0.55 Mt (Neil *et al.*, 2002). However, both reefs are also periodically influenced by flood plumes from the Burdekin, the largest river that drains into the GBR lagoon, situated approximately 80 km S of Cleveland Bay (McAllister *et al.*, 2000; Devlin and Brodie, 2005). During an average year, the Burdekin River delivers up to 0.45 Mt of bed load sediments and up to 4.5 Mt of wash load sediments to the GBR lagoon, with as much as 20 Mt of sediment delivered in a single event (Lewis *et al.*, 2006). The Burdekin River flood plumes can extend as far up as the wet tropics during extreme events, and it is estimated that approximately 5-10% of the fine sediments transported northwards are deposited in Cleveland Bay (Lewis *et al.*, 2006).

Coral reef development in Cleveland Bay is limited to its western end, possibly because sediment accumulation in its southern NE facing bay impedes reef growth (Lambrechts *et al.*, 2010). However, fringing reefs have developed in a number of enclosed bays on Magnetic Island and contain a diverse range of hard coral, soft coral and algae species (Bull, 1982; Mapstone *et al.*, 1992; Ayling and Ayling, 1998). A number of research studies have been conducted on these reefs, ranging from small-scale coral behaviour studies (Anthony, 2000; Sofonia and Anthony, 2008), to large-scale studies of the physio-environmental processes and its influence on community assemblages (Van Woesik *et al.*, 1995; Orpin *et al.*, 2004; Lambrechts *et al.*, 2010). Middle Reef and Virago Shoals, which are situated within the western regions of Cleveland Bay, represent the only nearshore reef and shoal in Cleveland Bay. In contrast, Halifax Bay contains at least six nearshore reefs and shoals (e.g. Pandora Reef), and fourteen high islands with fringing reefs. The availability of suitable substrate for reef initiation within Halifax Bay, most likely Pleistocene fluvial cobbles and pebbles, is regarded as the primary control on reef location (Larcombe *et al.*, 2001), however, high sediment resuspension rates and low sediment accumulation may also be a driving factor.

1.7 Overview of research methods

Field trips to Middle Reef and Paluma Shoals were undertaken from July 2008 to April 2011. The first year of data collection (2008) focused on establishing reef morphology from high resolution bathymetric surveys and benthic cover from GPS referenced transects (<30 sites per reef) that were distributed between depths and reef habitats (chapter 3). Surficial sediment samples and coral rubble samples were collected along each benthic transect. Sediments were analysed for particle grain size analysis, carbonate content and grain composition (chapter 4), and coral rubble samples provided information on bioerosion rates (chapter 8). Encrusting tiles (>300 deployed) were also placed at the start of half the benthic transects to determine encruster abundance, composition and carbonate production. The tiles were collected and replaced after a year in the field and provided data for the carbonate budget assessment quantified in chapter 8. The second year of data collection (2009) focused on sediment dynamics: hydrodynamic and turbidity data loggers were placed at key locations on Middle Reef and Paluma Shoals for up to three weeks, four times throughout the year to determine the hydrodynamic forces that lead to spatial and temporal variations in turbidity (chapter 5). Temporal and spatial variations in sedimentation were also evaluated, using a new field methodology developed to overcome problems associated with sediment traps typically used for such assessments. The new approach was based on paired sediment trays which proved to be successful not only in quantifying sedimentation rates from mid 2009 to the start of 2011, but also sediment resuspension and flux rates (chapter 6). Finally, from mid 2009 to mid 2010, 130 corals were stained *in situ* on Middle Reef using the Alizarin Red-S technique, and samples were collected after 3 to 4 months to provide data on coral growth rates for the primary framework builders (chapter 7).

1.8 Thesis structure and overview of data chapters

Chapter 2: This chapter reviews geological, palaeoecological and ecological data to assess key environmental controls on turbid zone reef occurrence, coral community composition and reef growth. The influence of terrigenous sediments on the rate and mode of reef growth is investigated, and I discuss some of the conflicting arguments about the vulnerability of turbid zone reefs to threats such as reduced water quality, disturbance events and projected environmental changes. The review identifies a number of knowledge gaps in the literature, which are largely focused on the role of terrigenous sediments in inshore reef growth, and highlights the importance of establishing relationships between sediment dynamics, benthic community responses and carbonate production to accurately assess inshore turbid reef health, growth and long-term stability.

Chapter 3: Detailed descriptions of benthic community assemblages on inshore turbid reefs are comparatively rare to those available for offshore clear-water reefs. This paucity is a reflection of the difficulties associated with data collection on inshore turbid reefs (low visibility, hazardous marine life), which has led to a lack of long-term data available for these reef communities. A detailed description of benthic community assemblages at Middle Reef was conducted, and spatial and temporal variations in benthic assemblages were evaluated to identify key environmental controls. A high resolution geomorphological model was constructed from detailed bathymetric surveys on to which benthic community assemblage data from GPS referenced transects were over-laid. This chapter provides a detailed study on reef geomorphology with benthic cover at a high spatial resolution for an inshore turbid reef on the GBR, and together with a similar data set on Paluma Shoals, provided the required data on benthic cover for the carbonate budget assessment in chapter 8.

Chapter 4: Sediments are likely to play an important role in reef growth and, yet, there have been few studies that characterise sediments, and document the relationship between sediments and benthic cover on inshore turbid reefs. Sediment deposits are important carbonate sinks that form a component of a reef's carbonate budget. However, in turbid coastal waters, terrigenous sediments will alter the sediment composition, influence benthic cover and potentially reduce carbonate production and reef growth. Therefore, it is important to understand the relationships between carbonate and terrigenous sediments, benthic cover and reef growth to determine if and when an inshore reef is threatened by increased terrigenous sediment loads. The objectives of this chapter were to examine the spatial distribution of sediments with reef morphology and benthic cover thereby establishing sediment/benthic cover interactions, and identify the main driving forces of sediment distribution. Surficial sediment samples were collected from Middle Reef and Paluma Shoals, and analysed for carbonate content, sediment composition and particle size. This chapter provided the necessary data on direct carbonate sediment production required for the carbonate budget assessment in chapter 8.

Chapter 5: Many corals on inshore turbid reefs have become heterotrophic due to large and rapid fluctuations in turbidity and, therefore, less dependent on light energy. However, the upper threshold limits to elevated turbidity, and additional stress effects from high sediment loadings such as burial of corals, are unknown partly due to differences in the extent of heterotrophic plasticity between coral species, but also partly due to the highly transient nature of sediments which creates a high level of spatial and temporal variability in turbidity. Spatial variations in turbidity are typically reported at the scale of 10's km, but in turbid coastal waters, large gradients in turbidity commonly occur over comparatively small distances (<1 km), which may lead to considerable changes in coral cover and diversity over a reef. The implications of large gradients in turbidity for benthic composition and distribution, and ultimately long-term reef development are unknown, but are likely to play an integral role. A detailed over-view of the hydrodynamic regime and corresponding turbidity is assessed for a sheltered and exposed site on Middle Reef and Paluma Shoals to determine spatial differences and associated driving forces. Wind data was found to be a reliable indicator of turbidity and was used to develop a model to predict temporal variations in turbidity.

Chapter 6: A greater understanding of sediment behaviour in marine ecosystems is vital in the assessment of reef growth and development. High sediment yields are considered a major threat to reefs, although there is growing evidence that benthic communities on inshore turbid reefs have adapted to high turbidity or/and sedimentation. Despite these adaptations, excessive sediment loads may still threaten inshore turbid reefs, but, current understanding of when these communities are at risk is unknown due to a lack of reliable data on sediment deposition, resuspension and transport. This lack of knowledge is partly due to the transient nature of sediments, and partly due to data collection techniques which have in the past largely relied on the use of sediment traps which over-estimate sedimentation rates and do not accurately reflect sedimentary conditions. A new approach based on sediment trays was developed that allows the sedimentation rate, sediment resuspension and the total mass of mobile sediments transported on to and off a site (termed the sediment flux rate) to be measured or calculated. Detailed quantitative analysis on the sedimentary regime provided the required data for the assessment of sediment dynamics in chapter 8.

Chapter 7: Inshore reefs close to heavily modified coastal catchments are threatened by both global (e.g. sea surface temperatures, ocean acidification) and local (sediment, nutrients) environmental changes, and are often considered to be vulnerable to reef degradation (Glynn, 1994). While there is some detailed knowledge on how these individual stressors influence benthic communities, less is known on the long-term effects of multiple stressors on carbonate production and inshore turbid reef growth and development. Corals are typically the main carbonate producer, and can be quantitatively assessed to indicate the longer-term consequences of changing environmental conditions. This chapter investigates coral growth rates and carbonate production of three corals, (*Acropora, Montipora, Turbinaria*), common to both inshore turbid and offshore clear-water reefs, studied *in situ* on Middle Reef. Data on coral growth rates are used in chapter 8 to determine carbonate production by corals for the carbonate budget assessment.

Chapter 8: Coral reef growth is dependent on carbonate production by calcifying organisms, such as corals, and carbonate destruction by biological (e.g. bioeroders) and physical erosion. Hence, the balance between carbonate production and destruction, quantified as the carbonate budget, is critical to reef growth and development. On turbid reefs, terrigenous sediments will also influence the rate and mode of reef growth as evidenced by the large volumes of terrigenous sediments observed in reef cores, and also the dominance of sediment tolerant coral species both in historic and modern community assemblages. However, the lack of quantitative data on terrigenous sediments, carbonate production and reef growth, limits understanding of reef growth within terrigenous sedimentary settings. To address this knowledge gap a carbonate budget and terrigenous sediment model, that quantified allochthonous sediment inputs on to, within and off the reef, was developed for Middle Reef and Paluma Shoals. This study provides the first carbonate budget study for the GBR, and the first to incorporate a quantitative analysis of terrigenous sediment dynamics onto, within and off a reef system in the development of a quantitative reef growth model. Data from chapters 2, 3 and 6 are used to construct the carbonate budget, and data from chapters 3, 4 and 5 are used to construct the sediment dynamics model.

Chapter 9: Conclusions.

2. CORAL REEFS OF THE INNER TURBID GREAT BARRIER REEF: A GEOLOGICAL PERSPECTIVE ON OCCURRENCE, COMPOSITION AND GROWTH

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2.1 Abstract

Investigations of the sedimentary context in which turbid zone reefs exist, both in the modern and fossil reef record, can inform key ecological debates regarding species tolerances and adaptability to elevated turbidity and sedimentation, as well as critical geological and palaeoecological questions surrounding longer-term coral-sediment interactions and reef growth rates. Here I review current knowledge about turbid zone reefs from the inner Great Barrier Reef (GBR) to consider these issues, and specifically to evaluate the nature of reef growth in the period prior to European settlement, and their future prospects. Turbid zone reefs on the GBR are relatively well known compared to those in other reef regions. They occur within 20 km of the mainland coast where reef development may be influenced by continual or episodic terrigenous sediment inputs, fluctuating salinities (24-36 ppt), and reduced water quality through increased nutrient and pollutant delivery from urban and agricultural runoff. Individually, and in synergy these environmental conditions are widely viewed as unfavourable for sustained and vigorous coral reef growth, and thus these reefs are widely perceived as marginal compared to clear water reef systems. However, recent research has revealed that this is not the case, and that many turbid zone reefs are resilient systems with relatively high coral cover (>30%) and distinctive community assemblages dominated by fast growing (*Acropora, Montipora*) and/or sediment tolerant species (*Turbinaria*, *Goniopora, Galaxea, Porites*). Palaeoecological reconstructions using reef cores show that community assemblages are relatively stable at millennial timescales, and that many reefs are actively accreting (average 5-10 mm/year) where accommodation space is available, despite recent anthropogenic pressures. Turbid zone reefs challenge traditional views on environmental conditions required for active reef growth, and provide an analogue for the earliest reef initiation on the outer-shelf of the GBR. Terrigenous sediments are a dominant influence on

turbid zone reef occurrence, composition and growth, and, therefore, the assessment of their future prospects will require a detailed understanding of the sedimentary regime.

2.2 Introduction

Coral reefs that develop in turbid water settings where suspended sediment loads are frequently above those normally associated with vigorous reef growth are described as turbid zone reefs (Roy and Smith, 1971; Partain and Hopley, 1989; Perry, 2003; Perry and Smithers, 2006). Turbid zone reefs are typically situated in nearshore coastal settings where they may be directly or indirectly exposed to terrigenoclastic sediments through sediment deposition and accumulation, or by sediment resuspension and elevated turbidity. High levels of sedimentation (>10 $mg/cm^2/day$; Rogers, 1990) can increase coral mortality by smothering and burial (Loya, 1976), reduce larval settlement, and increase the prevalence of tissue infections (Bruno *et al.*, 2003; Nugues and Callum, 2003; Fabricius, 2005), and high levels of turbidity (>10 mg/L) reduce light availability for photosynthesis and energy production (Rogers, 1990; Wolanski and De'ath, 2005). Nutrient (e.g. nitrogen and phosphate) concentrations may also be elevated near the coast due to increased land and river runoff. Elevated nutrients threaten reefs by causing algal proliferation (Fabricius, 2005), increasing the abundance of bioeroding filter feeders (Hallock, 1988), and raising the frequency and severity of coral disease (Bruno *et al.*, 2003). Consequently, where clear-water environmental conditions are used as a benchmark, environmental conditions inshore are widely considered sub-optimal for ‘healthy’ coral reef growth. As such, it is commonly claimed that turbid zone reefs are stressed and/or degraded (Neil *et al.*, 2002; McCulloch *et al.*, 2003; Woolridge *et al.*, 2006; Hughes *et al.*, 2011). However, many turbid zone reefs have high coral cover (>30 %) and diversity (>100 species; Veron, 1995; DeVantier *et al.*, 2006), contain temporally stable community assemblages over centennial to millennial timescales (Riegl *et al.*, 1995; McClanahan and Oburu, 1997; Ayling and Ayling, 1999a; Perry *et al.*, 2008; Perry *et al.*, 2009), have actively and rapidly accreted (Smithers and Larcombe, 2003; Perry and Smithers, 2006; Palmer *et al.*, 2010), and are able to recover quickly from periodic setbacks such as flood events and cyclones to which they are regularly exposed (Ayling and Ayling, 2005; Browne *et al.*, 2010).

Turbid zone reefs occur within a number of geomorphic settings ranging from wave protected and sheltered muddy embayments to open coastal and high island settings, and have initiated over substrate types which vary from mobile alluvial and subtidal sands and gravels, to hard rocky substrates (Fig. 2.1). They are morphologically diverse but form a range of fringing, nearshore and shoal reef structures. Kennedy and Woodroffe (2002) provide a review of global fringing reef morphology and growth, and have found that many fringing reefs initiated as nearshore reefs and then became shore-attached either through shorewards progradation of the leeward reef edge (e.g. King Reef, central GBR; Hopley *et al.*, 2007) or coastal progradation towards the reef (e.g. Yule Point, far north GBR; Bird, 1971).

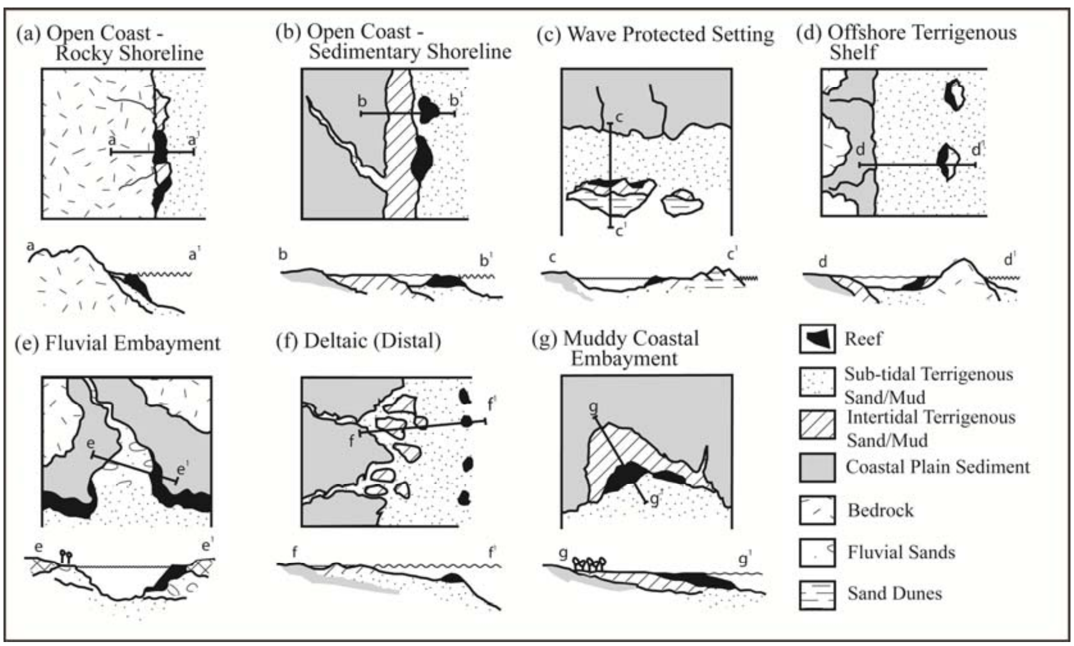

Figure 2.1: Conceptual model of turbid zone reef growth in different marine settings (a) open coast, rocky shoreline, (b) open coast, sedimentary shoreline, (c) wave protected, (d) offshore terrigenous shelf, (e) fluvial embayment, (d) distal to river delta, and (g) muddy coastal embayment.

Varied reef morphology from site to site reflects differences in factors including: substrate type and pre-existing topography, water depth and sea level history, hydrodynamic setting, and sedimentation and turbidity regimes. In open coastal settings reefs may initiate over hard substrates such as at the base of steep rocky headlands (e.g. Great Palm Island, central GBR; Hopley *et al.*, 2007), or on more mobile sediments along a gradual gradient at the base of a beach (e.g. Paluma Shoals, central GBR; Smithers and Larcombe, 2003). Turbid reefs have also developed in wave-protected locations such as on the leeward side of submerged rocky outcrops in deeper water (<20 m) (e.g. Sodwana Bay, South Africa; Schleyer and Celliers, 2003) or on high islands further offshore where low energy conditions permit the development of extensive intertidal sands and rubble flats (e.g. Inhaca Island, southern Mozambique; Perry, 2005). Turbid reefs have also initiated proximal to large rivers within fluvial embayments (e.g. Discovery Bay, Jamaica; Mallela *et al.*, 2004) where gradients in river discharge influence community composition, as well as offshore from river deltas beyond which large quantities of suspended sediments sustain high turbidities (e.g. Bay of Baten, Indonesia; Hoitink and Hoekstra, 2003). High turbidity and limited light penetration within muddy embayments, where wave energy is reduced, will also influence the depth to which coral cover can extend, and therefore controls reef growth and morphology (e.g. Phuket, South Thailand; Tudhope and Scoffin, 1994).

Over the past decade research on turbid zone reefs has intensified to include ecological, palaeoecological and geological studies, due to growing concerns over their exposure to both local threats such as increased sediment, nutrient and pollutant delivery (Cooper and Fabricius, 2007; De'ath and Fabricius, 2010), and global threats such as rising sea surface temperatures (coral bleaching) and ocean acidification (Table 2.1; Hughes *et al.*, 2003). Ecological studies suggest that turbid zone reefs are more vulnerable to reef degradation than their clear-water mid- and outer-shelf reef counterparts (Cooper and Fabricius, 2007; Fabricius *et al.*, 2007; Fabricius *et al.*, 2008). However, evidence from reef cores from Holocene turbid zone reefs indicate that many turbid zone reefs initiated and continued to grow within a naturally high sedimentary setting similar to contemporary conditions (Perry, 2003; Smithers and Larcombe, 2003; Perry *et al.*, 2008), suggesting a degree of resilience to sedimentation and turbidity. Furthermore, radiometrically-dated reef cores indicate the regional demise of turbid zone reefs on the

Table 2.1: Summary of natural and anthropogenic stressors for turbid zone reefs and the potential consequences of these stressors.

Environmental pressures		Consequences	References
Natural			
Sediment load	Sedimentation	Smothers and bury corals	Loya, 1976
		Reduces surface area for larval settlement	Fabricius *et al.*, 2005,
		Increases coral juvenile mortality	Wittenberg & Hunte, 1992
		Increases disease prevalence	Bruno, 2003
		Reduces energy for other metabolic functions e.g. reproduction, immunity and coral growth	Rogers, 1990, Davies, 1991
	Turbidity	Lowers light availability for energy production	Rogers, 1990
Freshwater	Low salinity	Causes freshwater bleaching	Devantier *et al.*, 1997
Water temperature	Higher during summer months	Causes bleaching	Berkelmans *et al.*, 2004
Physical damage	Storms, cyclones etc.	Leads to coral breakage, and loss of coral cover and diversity	Fabricius *et al.*, 2008
		Shifts community assemblage composition	Done & Potts, 1992
		Redistributes carbonates	Fabricius *et al.*, 2007
		Reduces structural complexity	Done, 1992
Anthropogenic			
Nutrients	Nitrates, phosphates etc.	Decreases water clarity due to algal blooms	Fabricius, 2005
		Increases macro-algal cover and may lead to an algal-phase shift	De'ath & Fabricius, 2010
		Increases bioeroders and other heterotrophic organisms e.g. sponges which compete with corals for space	Hallock, 1988, Hutchings *et al.*, 2005
		Increases phytoplankton availability which has been linked to *Acanthaster planci* outbreaks	Fabricius *et al.*, 2010
		Stresses corals and potentially reduces reproduction and coral growth rates	Tomascik & Sanders, 1987
Pollutants	Agrochemicals, pesticides etc.	Reduces the success rate for coral larval development	Markey *et al.*, 2007
Physical damage	Boat groundings and anchor damage etc.	Damages corals and may lead to coral death	Wachenfeld *et al.*, 1998
Harvesting	Fishing, lobster pots etc.	Effects trophic cascades and may lead to decline in reef health	Jackson *et al.*, 2001
Coastal development	Sedimentation	See sedimentation effects	
Dredging	Turbidity	See turbidity effects	
	Release of pollutants	See pollutant effects	
Invasive species	Ship fouling	Decreases coral community abundance and diversity	Bauman et al., 2010
Future climate change scenarios	Higher rainfall	Increases the delivery of sediments, nutrients, pollutants and freshwater to inshore regions	Goldberg & Wilkinson, 2004, Fabricius *et al.*, 2007, Hoegh-Guldberg, 1999, Hughes *et al.*, 2003
	Higher mean SST	Increases sea surface temperature fluctuations inshore which may lead to increased levels of coral bleaching	
	Ocean acidification	Reduces ocean pH will lead to carbonate dissolution, weakening of carbonate organisms and increase the fragility of coral reef ecosystems	

inner GBR several thousand years ago but also record a regional recovery following a hiatus of several hundred years: a recovery that extends to the present despite the modern day sedimentary regimes and anthropogenic threats (Perry and Smithers, 2011). These palaeoecological and geological studies provide a context for current community change and indicate that turbid zone reefs are more robust ecosystems than generally considered.

There is mounting evidence that turbid zone reefs are resilient ecosystems that contain individual corals and community assemblages that are tolerant to unfavourable environmental conditions. The first comprehensive assessment of a turbid zone reef was performed at Low Isles Reef, northern GBR, in 1928 by the Great Barrier Reef Committee and the Royal Society of London (Hopley *et al.*, 2007). Low Isles has been further monitored over the intervening years (Stephenson *et al.*, 1958; Fletcher, 2000; Frank and Jell, 2006; Frank, 2008) and has provided some of the first evidence to suggest that many coral reef communities can tolerate sediment loads and turbidity regimes that are well above those which negatively affect clear-water reefs. However, despite recent advances in our understanding of these ‘marginal reefs’, knowledge of coral community persistence, of the influence of high sedimentation and turbidity on both coral community assemblages and reef growth, and on the mode and rate of reef growth remains poor. Furthermore, it is unclear how resilient turbid zone reefs are given increasing human pressures and associated stressors.

Here I review geological, palaeoecological and ecological data to assess key environmental controls on turbid zone reef occurrence, coral community composition and reef growth. The influence of terrigenous sediments on the rate and mode of reef growth is investigated, and I discuss some of the conflicting arguments about the vulnerability of turbid zone reefs to threats such as reduced water quality, disturbance events and projected environmental changes. Data from the GBR augmented with data from the Caribbean, Asia and Africa, are used to address these issues. The GBR is the most comprehensively studied coral reef system in the world, and has provided most of the data currently available on turbid zone reefs, both modern and in the recent geological record. Since the 1980’s studies on turbid zone reefs of the GBR have become more numerous and diversified to include small-scale assessments of coral growth rates to broad scale assessments of disturbance events, and today over 20 inshore turbid reefs are regularly monitored by the Australian Institute of Marine Science (AIMS) (Fig. 2.2; Table 2.2). In addition, over 70 reef cores have been collected to provide the most extensive data available on turbid zone reef growth and development. These data provide important links between reef ecology and geology, and are used to address controversial issues regarding the influence of anthropogenic activities on their long-term reef development.

Table 2.2: Reference list for Figure 2.2 which illustrates the location and type of study carried out on inshore turbid reefs on the GBR.

No.	Reference	No.	Reference	No.	Reference
1	Anthony, 2000	28	Done *et al.,* 2007	55	Partain & Hopley, 1989
2	Anthony, 2006	29	Endean *et al.,* 1989	56	Perry & Smithers, 2006
3	Anthony & Fabricius 2000	30	Fabricius *et al.,* 2003	57	Perry *et al.,* 2008
4	Ayling & Aying, 1985	31	Fabricius *et al.,* 2005	58	Perry *et al.,* 2009
5	Ayling & Ayling, 1986	32	Fisk & Harriot ,1986	59	Perry *et al.,* 2010
6	Ayling & Aying, 1991	33	Frank, 2008	60	Risk & Sammarco, 1991
7	Ayling & Ayling, 1995	34	Frank & Jell, 2006	61	GBRE, 1928-1929
8	Ayling & Ayling, 1996	35	Graham, 1993	62	Sammarco & Risk, 1990
9	Ayling & Ayling, 1998	36	Harriot & Fisk, 1990	63	Smith *et al.,* 2005
10	Ayling & Ayling, 1999	37	Hedley, 1925	64	Smithers & Larcombe, 2003
11	Ayling & Ayling, 2005	38	Hopley *et al.,* 1978	65	Smithers & Larcombe, 2006
12	Ayling *et al.,* 1998	39	Hopley *et al.,* 1983	66	Sofonia & Anthony, 2008
13	Baird & Marshall, 2002	40	Hopley & Barnes, 1985	67	Van Woesik & Done, 1997
14	Bird, 1971	41	Johnson *et al.,* 1985	68	Van Woesik, 1992
15	Browne *et al.,* 2010	42	Johnson & Risk, 1987	69	Van Woesik *et al.,* 1995
16	Bull, 1982	43	Jones *et al.,* 2008	70	Van Woesik *et al.,* 1999
17	Chappell *et al.,* 1983	44	Kaly *et al.,* 1994	71	Wachenfeld, 1995
18	Cheal *et al.,* 2001	45	Kleypas, 1996	72	Weber *et al.,* 2006
19	Chin & Ayling, 2000	46	Larcombe & Costen, 2001	73	Weeks *et al.,* 2008
20	Cooper *et al.,* 2008b	47	Larcombe *et al.,* 1995	74	Whinney, 2007
21	Cooper *et al*., 2007b	48	Larcombe & Woolfe, 1999	75	Wolanski *et al*., 2005
22	Cooper *et al.,* 2008a	49	Lewis, 2005	76	Wolanski *et al.,* 2008
23	Devantier, 1995	50	Lough & Barnes, 1992		
24	Devantier *et al.,* 1997	51	Lough & Barnes, 1995		
25	Devantier *et al.,* 1998	52	McCulloch, 2003		
26	Done, 1982	53	Orpin *et al.,* 2004		
27	Done & Potts, 1992	54	Palmer *et al.,* 2010		

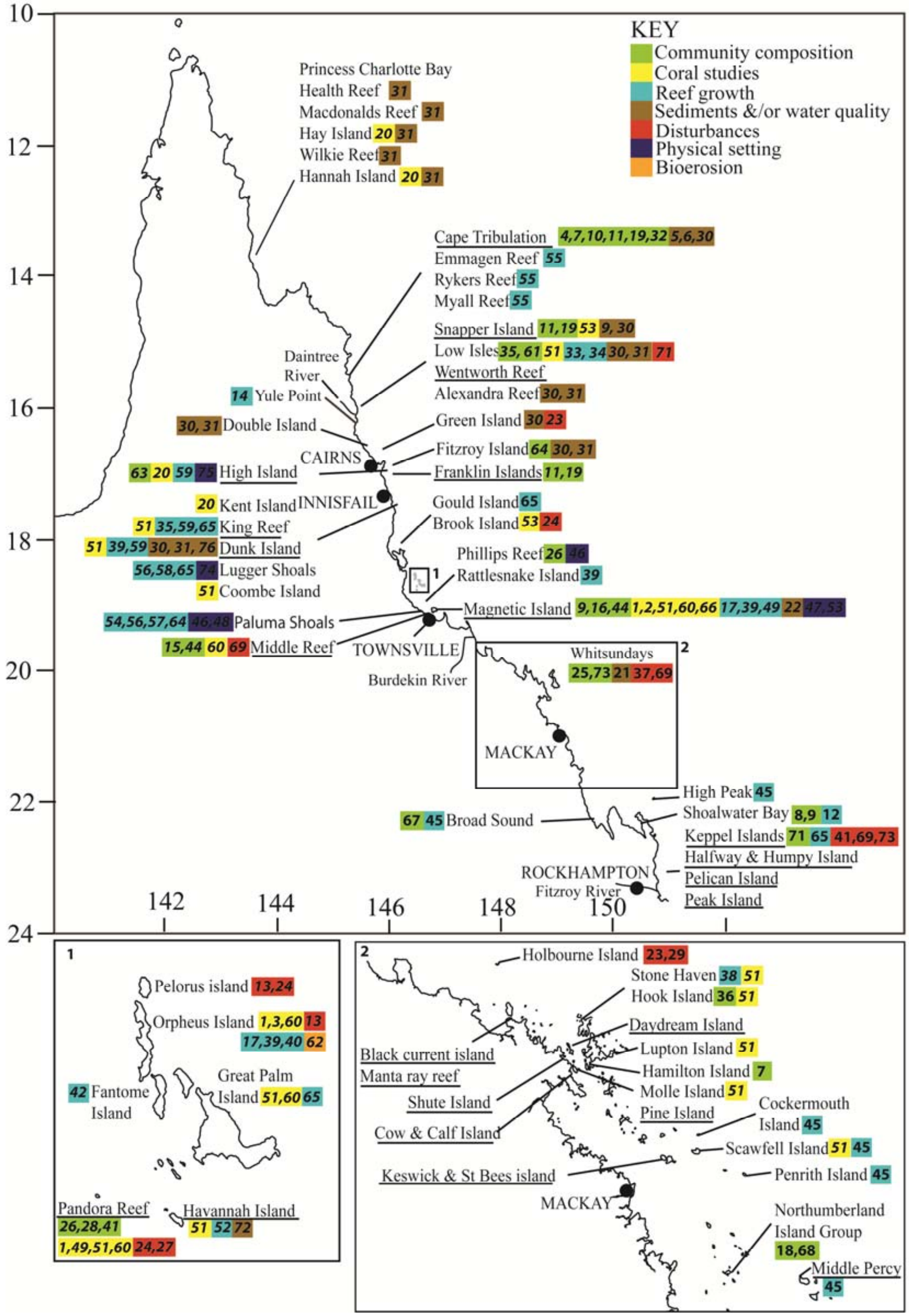

Figure 2.2: Surveys conducted on fringing and nearshore turbid reefs on the inner GBR shelf. Coloured boxes denote the type of survey and numbers refer to source in Table 2.2. Long-term monitoring sites of the Australian Institute of Marine Sciences (AIMS) are underlined.

2.3 Distribution of turbid zone reefs on the inner GBR

Turbid zone reefs on the GBR occur in shallow (<20 m), inshore lagoon waters within 20 km of the coast, where environmental conditions are often considered marginal for reef growth. The substrate within the inshore zone includes a thick (5-10 m) wedge of terrigenous mixed sand and mud referred to as the inshore sediment prism (ISP) derived from long-term fluvial inputs deposited on the shelf during the last sea-level lowstand together with those reworked shorewards during the post-glacial transgression. The inshore zone is one of three shelf parallel sedimentary zones on the GBR shelf and is distinct from the mid-shelf (20–40 m) and outer sedimentary zones (40–80 m) which are starved of terrigenous sediments (Fig. 2.3; Belperio, 1988; Larcombe and Carter, 2004). Numerous coral reefs dominate the outer zone but in the mid-shelf zone they are generally restricted to fringing reefs surrounding high islands (Maxwell and Swinchatt, 1970; Larcombe and Carter, 2004). The distribution and morphological development of coral reefs within the inner sedimentary zone is well known and understood, and has been reviewed in detail by Smithers *et al.* (2006) and Hopley *et al.* (2007). Based on bathymetric charts and available remotely sensed imagery it is estimated that there are approximately 900 inshore reefs (Hopley *et al.*, 2007) including both fringing reefs, and nearshore reefs and shoals, representing approximately a third of the reefs on the GBR.

2.3.1 Fringing reefs

Mainland fringing reefs are common north of Cairns and along the Whitsunday coastline where the local geology forms steep headlands and embayments to which fringing reefs are attached. Headlands provide stable and firm rocky substrates long considered to be optimal for reef initiation and growth (Veron, 1995). However, on the GBR many fringing reefs have developed within the embayments where suitable substrates were available, either at the bay head or at the base of beaches (e.g. King Reef, (Fig. 2.4a); Hopley *et al.*, 2007). Large rivers discharging freshwater and terrestrial sediments may locally and even regionally impede the development of fringing reefs, accounting for the absence of fringing reefs a considerable distance north of the Fitzroy and Burdekin Rivers (Fig. 2.2). By comparison the Whitsundays coastline is less affected by river discharge, improving fringing reef initiation and

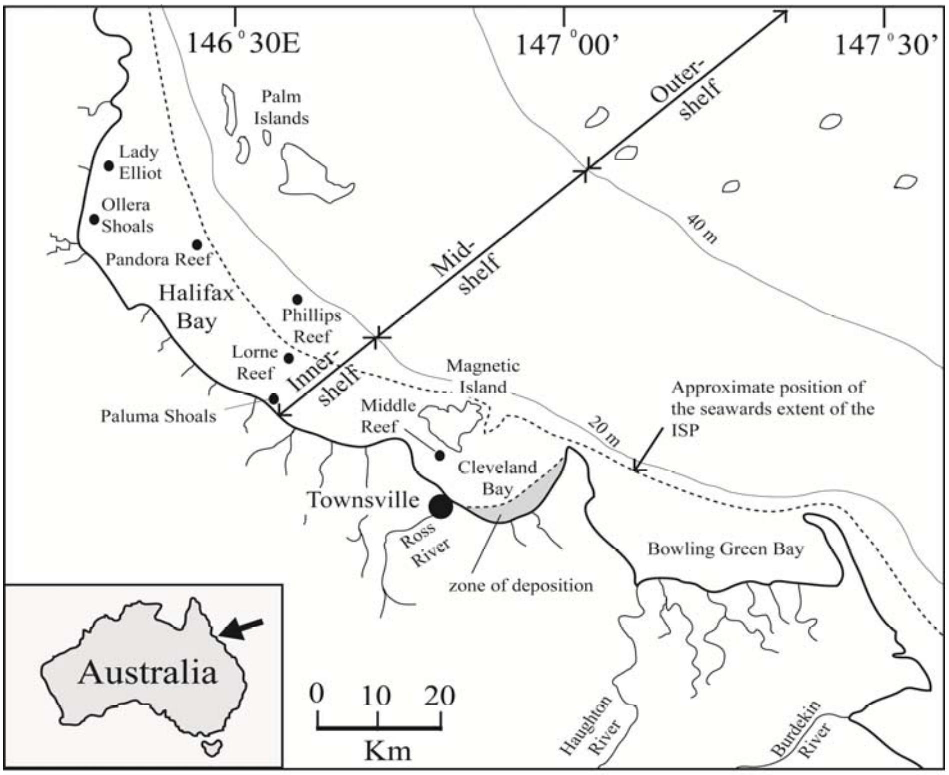

Figure 2.3: Three sedimentary zones (inner, mid- and outer-shelf) on the central GBR, and the location of six nearshore reefs in Halifax Bay.

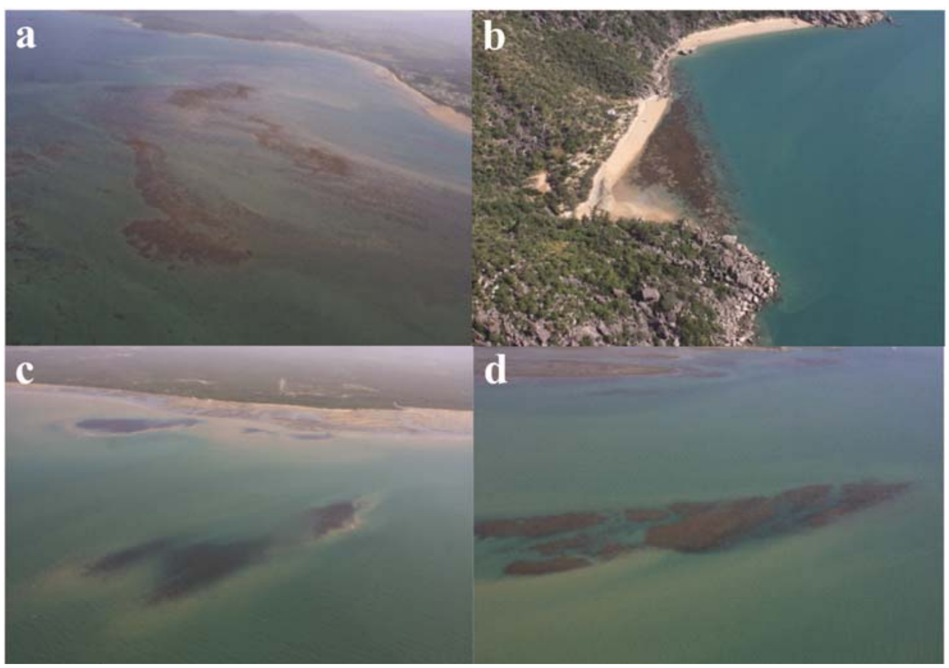

Figure 2.4: Arial photographs of turbid zone reefs within different geomorphic settings: (a) Wide beach base fringing reef, King Reef; (b) Headland attached fringing reef, Magnetic Island; (c) Nearshore shoal, Paluma Shoals; (d) Nearshore patch reef, Middle Reef.

survival. The negative influence of sediments, in particular high turbidity, on coral growth and carbonate production has limited reef growth around Broad Sound to the south of the Whitsundays, although in this region high turbidity is produced by sediment resuspension by strong tidal flows associated with a high tidal range (>10 m) (Kleypas, 1996; Van Woesik and Done, 1997). Inshore fringing reefs are also found on continental islands within and north of the Whitsundays (e.g. Five Beach Bay, Magnetic Island (Fig. 2.4b); Hopley *et al.*, 2007).

2.3.2 Nearshore reefs

Nearshore reefs and shoals occur close to the coast and are more evenly distributed along the GBR than fringing reefs (Hopley *et al.*, 2007). Although they are poorly represented in the literature, nearshore shoals represent an important reef type; many have high coral cover (>30%), are morphologically complex with a well-developed back reef, reef flat and reef slope (e.g. Paluma Shoals, Halifax Bay; Palmer *et al.*, 2010), and many have the potential to develop into 'true' reefs that build geomorphic structures with positive, wave resistant topography (Buddemeier and Hopley, 1988). Nearshore reefs and shoals can be found in turbid waters within open sedimentary coastal settings (e.g. Paluma Shoals; Fig. 2.4c), semi-protected coastal settings (e.g. Middle Reef, Cleveland Bay (Fig. 2.4d); Browne *et al.*, 2010) and occasionally within highly turbid muddy coastal embayments (e.g. Broad Sound; Kleypas, 1996). Less is known about nearshore reefs than fringing reefs despite their relatively common occurrence, as turbid waters hinder field research, and only a few detailed reef accretion and morphological descriptions are available. It was only relatively recently that submerged turbid reefs were discovered in the Gulf of Carpentaria, northern Australia, using multibeam swath sonar (Harris *et al.*, 2004), which suggests that they maybe more common than generally considered. Six nearshore reefs and shoals have been identified in Halifax Bay, north of Townsville (Fig. 2.3), an exposed bay with relatively high wave activity (>1 m wave height) and wind-driven resuspension of deposited sediments (Larcombe *et al.*, 2001). The availability of suitable substrate within Halifax Bay, usually Pleistocene fluvial cobbles and pebbles, is regarded as the primary control on reef location (Larcombe *et al.*, 2001), however, high sediment resuspension rates and low sediment accumulation is also an important factor.

2.4 Environmental controls on turbid zone distribution

Environmental controls on turbid zone reefs include the sedimentary and the hydrodynamic regimes, fluctuations in water quality linked to both natural (e.g. storm runoff or resuspension) and anthropogenic influences, and disturbance events such as cyclones and associated flood events (Table 2.3). The physical setting inshore, namely shallow water depths and often mobile sedimentary substrate, amplifies the effects of these environmental controls which, in combination, strongly influence the community composition and growth histories of turbid zone reefs. This section discusses the nature of these interacting influences using available data from the GBR.

2.4.1 Sediments

The sedimentary regime is a dominant control on community assemblages and turbid zone reef growth (Woolfe and Larcombe, 1999). Key aspects of the sedimentary regime relevant to turbid zone reef growth and survival include: the source and rate of sediment supply; coastal sediment transport; sediment deposition; and resuspension regimes. Sources of sediments to the inshore GBR include runoff from terrestrial catchments, and the resuspension and redistribution of shallow seabed sediments. The latter are composed of terrigenous sediments delivered to the coast by rivers, that have accumulated in coastal waters since sea level stabilised around 6,000 years ago (Larcombe and Woolfe, 1999b), as well as fine sediments worked landwards during the postglacial transgression. Sediment resuspension and turbidity is largely controlled by the hydrodynamic regime (waves, currents, tides); turbidity rapidly rises (>100 mg/L) during high wave energy events such as storms. However, turbid reefs located close (<10 km) to large rivers that supply large quantities of sediments to coastal regions (e.g. Lugger Shoals, 10 km north of the Tully River which delivers ~130,000 tonnes of sediment annually; Furnas, 2003) often experience extreme levels of prolonged turbidity (<3 days, Larcombe *et al.*, 2001; Whinney, 2007). For example, suspended sediment concentrations in coastal waters near the Tully River increased from <0.05 to 0.2 kg m^{-3} (measured at approximately 500 mg/L at Lugger Shoals; Whinney, 2007) near the surface during a 10 day flood event in 2007 with a further increase to 0.5 kg m^{-3} (measured as <1,500 mg/L at Lugger Shoals; Whinney, 2007) during strong winds

Table 2.3: Key differences in environmental setting, reef development and community assemblages between clear-water offshore reefs and inshore turbid reefs on the GBR.

	Clear-water offshore reefs			Inshore turbid reefs		
ENVIRONMENTAL CONTROLS	**Typical conditions**	**Description**	**References**	**Typical conditions**	**Description**	**References**
Oceanography	Oceanic conditions characterised by exposure to swell	High energy environments dominated by robust *Acropora* communities and high coralline algae cover	Done, 1986	Locally wind driven waves	Lack of coralline algae and robust *Acropora* communities reflect lack of oceanic swell	Giesters, 1977; Done, 1986
	Well mixed and flushed environments	Increased mixing due to up-wellings and large-scale turbulence generated by the flow around the reefs	Wang *et al.*, 2007	Low level of mixing and flushing rates	Large differences in seasonal water temperatures due to higher water residency times and increased distance from up-wellings	Wolanski, 1994
Sediment load	Low levels of sedimentation and turbidity	Sedimentation rate <10mg/cm^2/day and a turbidity <10 mg/L is considered to be 'normal' on reefs not subjected to human pressures	Rogers, 1990	High levels of sedimentation and turbidity	Sedimentation rate >10 mg/cm^2/day and turbidity levels from <10 mg/L to >50 mg/L	Riegl *et al*, 1995; Edinger *et al.*, 2000; Sofonia & Anthony, 2008
Freshwater	Stable salinity	~36 ppt	Lirman *et al.*, 2003	Extreme fluctuations	24-36 ppt. Low salinities can lead to freshwater bleaching events	Walker, 1981
Nutrient inputs	Low	Low chlorophyll *a* concentrations (<0.3ug/l)	De'ath & Fabricius, 2010	Potentially high	High nutrient inputs can lead to a shift to algal dominance; increased bioerosion; increased prevalence of coral disease	Hallock, 1988; Fabricius, 2005
Physical disturbance events	Variable	Physical disturbance events (e.g. cyclones) cause damage to greater depths on offshore reefs	Fabricius & De'ath, 2008	Variable	Potentially less resistant to physical damage due to fragile coral skeletons or less stable substrate type	Massel & Done, 1993; Fabricius & De'ath, 2008;
REEF DEVELOPMENT						
Reef initiation	Holocene	10,000 - 5,000 yBP	Hopley *et al.*, 2007	Holocene	6,000 – 1,000 yBP	Smithers *et al.*, 2006; Hopley *et al.*, 2007
Substrate availability	Hard substrate	Reefal foundations e.g. Pleistocene and Miocene reefs	Hopley *et al.*, 2007	Mixed	Most inshore reefs on the GBR have grown on sediment deposits within shallow coastal embayments	Smithers *et al.*, 2006
Average rate of reef growth	Variable	4-8 mm/year	Hopley *et al.*, 2007;	Variable	5-10 mm/year	Partain & Hopley, 1989; Kennedy & Woodroffe, 2002

Table 2.3 continued.

REEF DEVELOPMENT	Typical conditions	Description	References	Typical conditions	Description	References
Mode of growth	Carbonate	Internal structure dominated by shingle, rubble, *in situ* corals and course sand	Hopley *et al.*, 2007	Mixed	Reefal foundations, terrigenous sand and mud, *in situ* corals and rubble	Hopley *et al.*, 1983; Smithers *et al.*, 2006; Perry & Smithers, 2010
Surrounding bathymetry	Deep water (<50 m)	Coral reefs need sufficient light for photosynthesis, therefore restricted to ~50 m in clear water	Yentsch *et al.*, 2002	Shallow water (<15 m)	Reef growth restricted by shallow, turbid waters.	Hopley *et al.*, 2007; Perry & Smithers, 2010
					High level of wind driven resuspension of sediments	Larcombe *et al.*, 1995; Lou & Ridd, 1996
Sea level					Inshore reefs have been strongly affected by sea-level change which has influenced both substrate availability and reef morphology.	Kennedy & Woodroffe, 2002
COMMUNITY ASSEMBLAGES						
Composition	Variable to high coral diversity	~300 species High diversity provides resilience to change following a disturbance event	Veron, 1995; Ninio *et al.*, 2002	Variable to low coral diversity	<150 species Many inshore reefs have diverse coral communities, but many are also dominated by physiologically robust corals which may be more tolerant to change	Veron, 1995; DeVantier *et al.*, 2006
	High crustose coralline algae (CCA) cover	~35% CCA cover on the GBR	Fabricius & De'ath, 2001	Low CCA cover	<1% cover on the GBR	Fabricius & De'ath, 2001
Community age structure	Mixed	Community assemblages contain both young and old corals due to successful recruitment of coral larvae and low mortality rates	Done, 1982; Sweatman *et al.*, 2008	Mixed to older	Many inshore reefs characterised by large, older coral colonies which are capable of tolerating high sediment loads	Done, 1982; Sweatman *et al.*, 2008
	High recruitment and survival rates	More suitable substrate availability allows for more successful recruitment	Fabricius *et al.*, 2008	Low recruitment and survival rates	Less suitable substrate availability due to high sediment cover and high level of algal competition. High sediment loads can affect the survival of coral juveniles	Fabricius *et al.*, 2003

(Wolanski *et al.*, 2008). It is often during such events, that benthic communities on turbid zone reefs are threatened by sediments, and their survival will depend on the duration and intensity of the event as well the rate at which sediments accumulate on the reef, known to increase with depth (Wolanski *et al.*, 2005), and within sheltered reef habitats.

2.4.2 Hydrodynamics

The relationship between sedimentation, turbidity and turbid zone reef distribution on the GBR has been discussed by several authors (Done, 1982; Larcombe and Woolfe, 1999b; Orpin *et al.*, 1999; Woolfe and Larcombe, 1999), and it has been argued that the balance between sediment deposition and resuspension rather than the rate of sediment supply is critical to turbid zone reef distribution and survival. The balance between sediment deposition and resuspension is controlled by the hydrodynamic regime: sediment deposition is typically high in relatively low energy hydrodynamic settings where currents are reduced (<5 cm/sec) and wave energy is limited (<0.5 m wave height), whereas low levels of net sediment deposition occur in hydrodynamic settings where currents are stronger (>10 cm/s) and wave energy is higher (>1 m wave height). High rates of sedimentation (>10 mg/cm^2/day; Rogers, 1990) may smother and bury corals, and debilitate corals more than high turbidity (>10 mg/L; Rogers, 1990) particularly given that many coral species common on turbid reefs have adapted to low light levels produced by high turbidity (see section 2.6.1; Woolfe *et al.*, 1998; Anthony, 2000; Anthony, 2006). Turbid zone locations with high sediment resuspension and turbidity but low sedimentation are, therefore, more benign environments for turbid zone reef growth than high sedimentation (deposition) settings. For example, numerous nearshore and fringing reefs are located in Halifax Bay, immediately north of Cleveland Bay (Fig.2.3), which lies to the left of the ISP where waves resuspend sediments and currents transport sediments alongshore. Although these conditions facilitate an active sediment transport regime, deposition on reefs is generally low (Browne *et al.*, in review-a). In contrast, the north-east (NE) facing shoreline at the southern fringe of Cleveland Bay is a zone of net deposition (Fig. 2.3; Lou and Ridd, 1997; Lambrechts *et al.*, 2010), as it is protected from the stronger SE wind-driven waves, the major sediment transport process on the GBR inner shelf (Larcombe *et al.*, 1995; Larcombe *et* *al.*, 2001; Whinney, 2007), and also from the primary longshore currents which regionally transport sediments northward. As predicted by the Larcombe and Woolfe (1999a) model of reef growth in terrigenous-sedimentary settings, the southern shoreline of Cleveland Bay has high sedimentation and limited coral reef development.

2.4.3 Flood plumes

Flood plumes pose a greater threat to inshore turbid reefs than wind-driven resuspension events, according to some researchers (Wolanski *et al.*, 2008), due to the rise in sediment yields from coastal catchments since European settlement (Devlin and Schaffelke, 2009) and changes to the nature of sediments delivered. Coral reefs in Cleveland Bay are considered to be threatened by an increasing number of high turbidity events due to sediment accumulation within the southern regions at an estimated 60,400 tonnes per year from river discharge (Lambrechts *et al.*, 2010). However, the sediment layer inshore is more than four metres thick and has provided an abundant supply of material for resuspension by wind-driven waves prior to any recent increases in sediment delivery which are estimated to add <1.5 mm of sediment to the substrate each year (Larcombe and Woolfe, 1999a; b). Contemporary suspended sediment concentrations (SSC) in the bay are probably similar to levels over the past 6,000 years despite a heavily modified catchment and busy shipping port (Larcombe *et al.*, 1995). Furthermore, there is no direct evidence that suggests that coral reefs in the bay are being degraded from present day flood events, and there are even reports of increased coral cover over the last 10 years and rapid coral growth rates on nearby turbid zone reefs (Sweatman *et al.*, 2007; Browne, in review; Browne *et al.*, 2010). These findings highlight the importance of understanding both the hydrodynamic and sedimentary settings within the longer-term geological context when making broad assessments of reef health and growth trajectories.

The nature of sediments discharged into coastal waters during flood events as well as the hydrodynamic regime will influence the rate of sediment delivery, deposition and resuspension. Fine terrigenous sediments travel several 100's km while coarser sediments settle out of the water column within 10 km of the river mouth as salinities approach 10 ppt (Devlin and Brodie, 2005; Wolanski *et al.*, 2008). Flood plumes increase turbidity and limit light availability for reef benthos, but unlike resuspension events which increase suspended sediment concentrations from the sea floor, fine sediments are commonly stratified and confined to surface waters where mixing by waves is limited. The fate of these fine-grained sediments is largely unknown. However, they may be transported great distances along the inner-shelf and may eventually be deposited on mid-shelf reefs up to 60 km offshore (Lewis *et al.*, 2006; Brodie *et al.*, 2008). This is cause for concern given that fine sediments are often in conjunction with biologically active concentrations of herbicides and pesticides (Bainbridge *et al.*, 2009) and/or nutrients. When nutrients combine with suspended sediments 'marine snow' may form which, once deposited, can negatively influence benthic marine organisms to a greater degree than fine sediment deposition alone (Fabricius and Wolanski, 2000). However, deposited fine sediments are also more easily resuspended to greater depths than coarser sediments which may reduce sediment accumulation rates, particularly at deeper sites beyond the normal wave base (Wolanski *et al.*, 2005).

2.4.4 Water quality

Evidence directly linking changes in community coral composition to deteriorating water quality, in particular to increased sediment delivery, is tenuous as the naturally turbid conditions driven by wind resuspension (Larcombe *et al.*, 1995) and the natural disturbance regime (see section 2.7) confound identification of anthropogenically-driven sedimentation and turbidity events. The use of cores from massive corals, can in part, resolve some of these issues by determining when stress events occurred in a coral's life history and evaluating if these events correlate with anthropogenic activities. For example, increased grazing pressure on the Burdekin catchment in the mid 19th century has been linked to increased sediment delivery associated with catchment soil erosion to inshore regions based on trace elements in massive corals (Lewis *et al.*, 2007). However, reef cores as opposed to coral cores indicate firstly, that several turbid reefs have continued to vertically accrete rapidly post-European settlement, and secondly, that recent shifts in community assemblages and declines in reef-building capacity cannot necessarily be attributed to anthropogenic forcing (Perry *et al.*, 2009; Palmer *et al.*, 2010; Perry and Smithers, 2010; Perry and Smithers, 2011). Reef development will go through natural cycles of growth and quiescent phases, independent of anthropogenic activities (Perry *et al.*, 2008; Perry and Smithers, 2010; Perry and Smithers, 2011), and, therefore, a change in reef growth may simply reflect a reef entering a slow growth or 'turn-off' phase, as opposed to reef degradation caused by reduced water quality.

Low species richness inshore is often considered an indicator of excessive nutrient concentrations and sediment loads (Fabricius *et al.*, 2005; DeVantier *et al.*, 2006; Golbuu *et al.*, 2008), however, low species richness may also reflect naturally high sediment loads which have persisted for millennia on the inner-shelf GBR prior to modern day changes in water quality. Furthermore, true species richness may be underestimated on inshore reefs due to high turbidity and limited visibility during field assessments, which hinder surveys and species identification. However, species richness can be high (>50 species) inshore despite both naturally high turbidity and anthropogenic pressures (e.g. >80 coral species at Middle Reef situated within 3 km of a busy international port and heavily modified urban catchment, Fig. 2.2 (Browne *et al.*, 2010)). High species richness inshore, particularly where water quality is poor suggests that either hydrodynamic (e.g. wind driven flushing) conditions are preventing the build up of nutrients and contaminants, or inshore reef species may be tolerant of poor water quality. Given the growing number of studies that have demonstrated high and temporally stable species richness inshore (Larcombe *et al.*, 2001; DeVantier *et al.*, 2006; Browne *et al.*, 2010; Thompson *et al.*, 2011), a better indicator of water quality, given no other limiting factors, may involve the assessment of species composition and community structure (Cooper and Fabricius, 2007). For example, the abundance of corals more sensitive to sediments and nutrients such as *Pocillopora* (Hashimoto *et al.*, 2004), could provide a more appropriate measure of water quality.

2.5 Reef growth within the inner shelf

A range of environmental (see section 2.4) and ecological controls (see section 2.6) contribute to reef growth and development. This section discusses the importance of ecological influences and their interactions by examining the balance between carbonate production by reef organisms and removal by biological and physical mechanisms.

However, an underlying control on reef development is the probability of reef initiation, which is controlled largely by substrate availability (Kennedy and Woodroffe, 2002), light availability (Larcombe and Woolfe, 1999a) and recruitment potential. Figure 2.5 provides a summary of factors that contribute to turbid zone reef growth and development, which are discussed in more detail below.

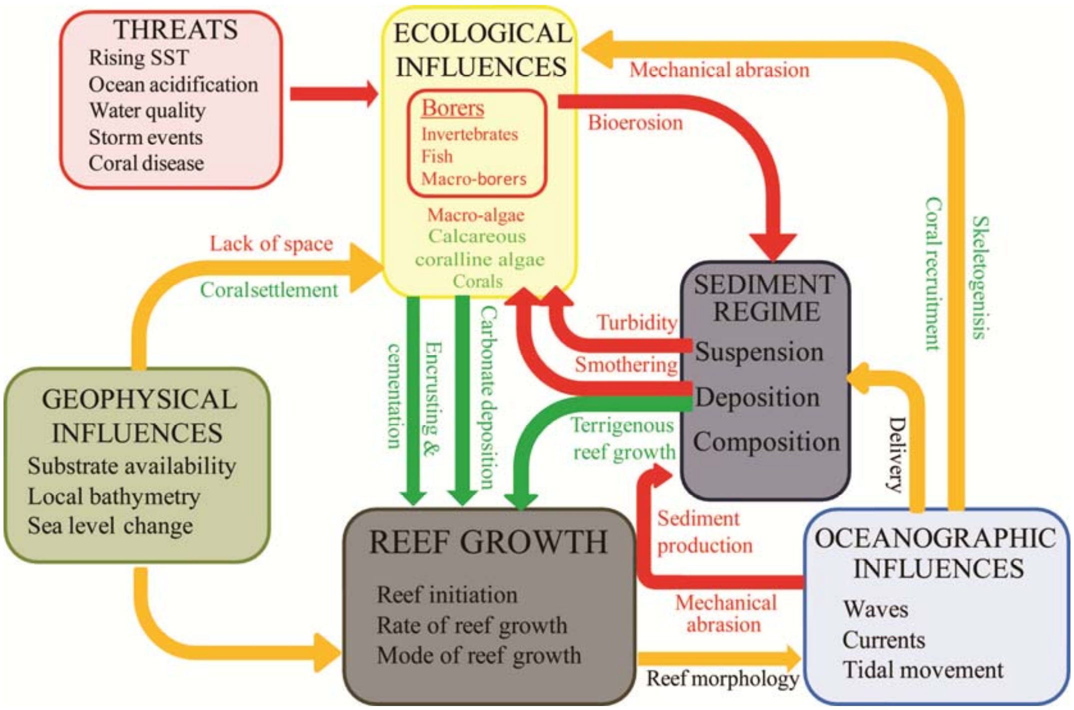

Figure 2.5: Inshore turbid reef initiation, growth and development are influenced by a number of complex processes including geophysical, oceanographic and ecological influences as well as the sedimentary regime. This model illustrates the main links between the key influences on inshore turbid reef growth and development. Green arrows represent positive processes for reef growth, red arrows represent negative processes, and yellow arrows indicate both negative and positive processes.

2.5.1 Controls on reef initiation

Turbid zone reefs are analogues for the earliest reef initiation on the outer-shelf of the GBR given that, prior to the Holocene sea-level transgression, controls on reef initiation would have been similar to those experienced by turbid zone reefs on the inner-shelf. Recent examinations of reef cores have identified two discrete episodes of reef initiation and growth: the first occurred approximately 8,000-5,000 yBP during the Holocene transgression-early highstand, and the second approximately 2,000 yBP (Smithers *et al.*, 2006; Perry and Smithers, 2011). The timing of the first of these two distinct reef initiation events, termed reef 'turn-on', has been broadly linked to changes in water depth as the sea flooded the continental shelf during the postglacial transgression, and the second event is interpreted to be related to sea-level stabilisation near its present level through the late Holocene (Perry and Smithers, 2010; Perry and Smithers, 2011). Reef initiation is widely perceived to be limited to hard substrates, but cores through many turbid reefs on the inner GBR suggest initiation is possible over a diversity of substrates, including unconsolidated sands, Pleistocene clays and 'coffee rock' (Hopley *et al.*, 1983; Smithers *et al.*, 2006; Roche *et al.*, 2011). For a few turbid zone reefs, reef initiation and subsequent reef growth has been largely controlled by the position of the ISP: in regions where wave energy was low near-shore, sediments accumulated and the ISP became shore attached preventing reef initiation near the coast. However, where the coast was exposed to SE winds, wave resuspension limited deposition and maintained a corridor of low sedimentation between the ISP and the shoreline where reefs could initiate if suitable substrates were available. As sea level has changed over the Holocene the ISP has migrated across the shelf influencing the position of this inshore corridor of reef initiation potential (Larcombe and Woolfe, 1999a).

2.5.2 Reef growth

Turbid zone reefs that have vertically aggraded since sea level stabilised on the GBR (~6,500 yBP ago; Carter and Johnson, 1986) have done so by rapidly accumulating both carbonate and terrigenous sedimentary material (Woolfe and Larcombe, 1999; Perry *et al.*, 2008; Perry *et al.*, 2009). In contrast, clear-water reefs are largely reliant on the accumulation of carbonate material produced by calcifying organisms (e.g. corals). The accumulation of both carbonate and terrigenous material on turbid zone reefs has led to rapid rates of vertical reef growth (average 5-10 mm/year, determined by radiometric dating of a number of reef cores) which in some cases has exceeded rates measured on mid- and off-shelf clear-water reefs (average 4-8 mm/year; Table 2.3). The accumulation of terrigenous and carbonate sediments provides a distinctive reef growth signature, which can be used to identify reefs that in the past grew in high terrigenous load sedimentary settings (Perry and Smithers, 2006; Perry and Hepburn, 2008; Perry and Smithers, 2009).

Reefs that develop under terrigenous sedimentary influences are subjected to spatial and temporal variations in sedimentation and turbidity which will result in marked differences in the rate and mode of growth between reefs. Fringing reefs proximal to major rivers may initiate on alluvial fan gravel deposits, and rapid reef growth is due to the accumulation of both alluvial and reef sediments (e.g. Cape Tribulation situated close to the Daintree River vertically accreted at a rate of 3.5 – 5.1 mm/year since reef initiation in 7,800 yBP; Partain and Hopley, 1989). Fringing reefs distal to major rivers, such as those on high-islands, may initiate on siliclastic sediments. For example, the low elevation fringing reefs on the protected leeward side of Dunk Island on the central GBR, initiated on unconsolidated inter-tidal siliclastic sediments which had been actively reworked prior to reef establishment approximately 1,600 yBP (Perry and Smithers, 2010). The reef reached sea-level rapidly (by 1,300 yBP on the landward margin) due to rapid reef accretion and limited accommodation space (<3 m), and has since formed a well-developed reef flat, characteristic of a reef approaching reef senility (Smithers and Larcombe, 2003; Perry and Smithers, 2011). In contrast, Paluma Shoals, also situated in a shallow-water setting (<4 m LAT), distal to a large river but within an exposed coastal setting, initiated over Pleistocene clays approximately 1,200 yBP, and is still actively accreting (Smithers and Larcombe, 2003; Perry and Smithers, 2011). The reef is in its early evolutionary stage and has grown at a rate of 1.1 – 1.8 mm/year under net fine-grained terrigenous sedimentation and high turbidity conditions (Smithers and Larcombe, 2003; Palmer *et al.*, 2010). These examples highlight variations in the timing of reef initiation, substrates available for reef initiation, and the rate and mode of reef growth.

To further understand of how turbid reefs have grown within these settings, two conceptual models have been developed: a terrigenous reef growth model presented by Woolfe and Larcombe (1999a) and a growth model based on key reef processes developed by Kleypas *et al.* (2001) which has a broader application but can be applied to turbid zone reef growth. The terrigenous reef growth model depicts the balance between the accumulation of terrigenous sediments on a reef, together with carbonate production and removal to schematically demonstrate how reefs can persist where turbidity is high (Fig. 2.6a; Woolfe and Larcombe, 1999). It recognises that reef growth is not just based on the balance between carbonate production and destruction, but also depends on additional additive processes, such as terrigenous sediment deposition, and destructive processes such as sediment removal. The model provides a useful tool for

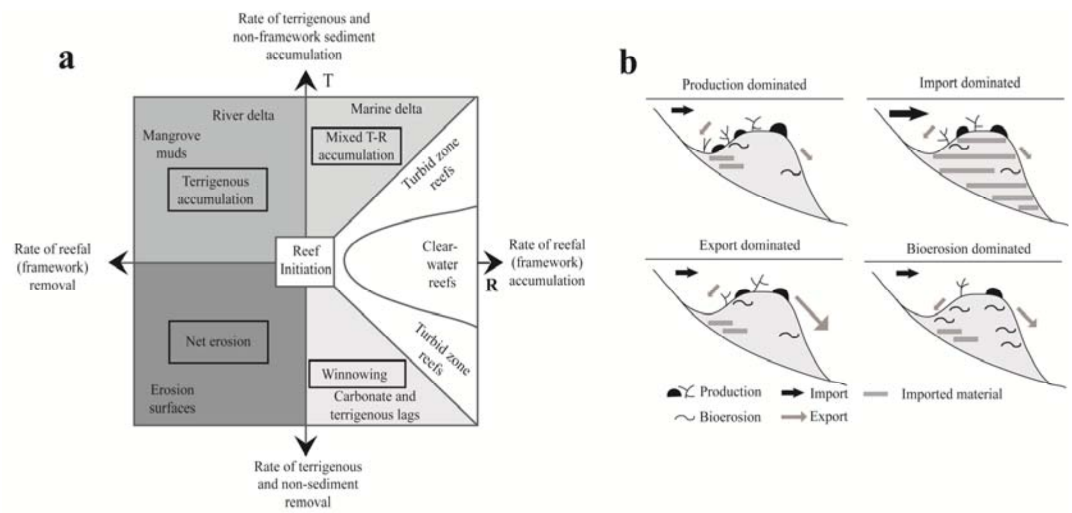

Figure 2.6: Conceptual reef growth models adapted from (a) Woolfe and Larcombe 1999 which recognises the importance of terrigenous accumulation as well as removal, and (b) Kleypas *et al.* 2001 which classifies reefs as either production-dominated, sediment-import-dominated, sediment-export-dominated or bioerosion-dominated.

predicting long-term reef growth patterns if environmental variables, particularly the sedimentary regime, should change. The second conceptual model by Kleypas *et al.* (2001) focuses on how much of the carbonate produced on a reef remains within that system and how much is broken down and lost, and classifies reefs as either production-dominated, bioerosion-dominated, sediment-import-dominated or sediment-export-dominated (Fig. 2.6b). Although these models were published more than a decade ago they remain conceptual and unsupported by data, reflecting the paucity of detailed data available on rates of carbonate production and removal, sediment import and export rates, and how terrigenous sediments influence the rate of carbonate production, deposition, and removal.

2.6 Intrinsic controls on reef growth and development

The rate of carbonate production and accumulation, which influences the rate and mode of reef growth and development, is partly controlled by the coral community, the primary carbonate producers, and the intrinsic controls that influence community assemblages and their distribution. Modern coral community assemblages observed on turbid reefs on the GBR have adapted to their sedimentary setting and are, therefore, distinctive from their clear-water counterparts (Table 2.3). These adaptations vary both among species and between coral families, with some corals more adapted to high sedimentation rates, whereas others are more suited to high turbidity and low light environments. As such, spatially variable sedimentary regimes result in heterogeneously distributed community assemblages which are also reflected in the Holocene reef cores (Smithers and Larcombe, 2003; Palmer *et al.*, 2010; Roche *et al.*, 2011). However, throughout reef growth and development, the dominant coral species are temporally stable, at least until sea level is reached where the influence of exposure during low tide results in a different assemblage of corals.

2.6.1 Coral assemblages and adaptations

Many coral species in turbid zone settings have developed either morphological and/or physiological adaptations that enable them to cope with high sediment loads that negatively affect corals and coral reefs normally exposed to low sediment influx (Stafford-Smith and Ormond, 1992). For example, *Turbinaria mesenterina* is highly abundant on inshore turbid reefs on the GBR and is well adapted to elevated sedimentation rates and turbidity levels (Sofonia and Anthony, 2008). *Turbinaria* is morphologically plastic (Riegl *et al.*, 1996), and under high sedimentation regimes, develops a characteristic funnel shape which concentrates sediment at the base of the funnel and away from actively calcifying areas of the colony. Other species such as *Porites* spp are tolerant to sedimentation rates of ~10 $mg/cm^2/day$, a rate previously believed to impede coral growth (Rogers 1990). To survive under these conditions *Porites* secretes a mucus coating which traps sediments but is easily sloughed off by waves and currents (Gleason, 1998). Other species common on turbid reefs, such as *Goniastrea* have adapted to high turbidity and low light through heterotrophic feeding off particulates in the water column at a rate that is up to four times greater than their conspecies on less turbid (<1 mg/L) mid-shelf reefs (Anthony, 2000). These spatially variable differences in adaptations to environmental conditions between individuals or geographic communities of the same coral species indicates that certain corals have an intrinsic ability to adapt to conditions previously considered detrimental to coral growth. These robust and resilient corals dominate turbid reef community assemblages throughout reef development (Perry *et al.*, 2008; Roche *et al.*, 2011).

2.6.2. Coral assemblage distribution and reef growth

The balance between sedimentation and turbidity, which fluctuates both spatially and temporally depending on exposure to wave energy and the tidal cycle, will influence community distribution and reef growth. For example at High Island, a turbid zone reef located 5 km offshore from the north Queensland coast, the depth of the sediment resuspension zone extended to 12 m on the windward reef slope and just 5 m on the lower energy leeward reef slope (Fig. 2.7). Below these depths, limited sediment resuspension and flushing resulted in sediment accumulation and a decline in coral cover from >20 % in the resuspension zones to <5 % in the depositional zones. Limited resuspension and flushing of sediments also occurs within protected internal basins or lagoons that form on some inshore turbid reefs (e.g. Middle Reef; Fig. 2.8).

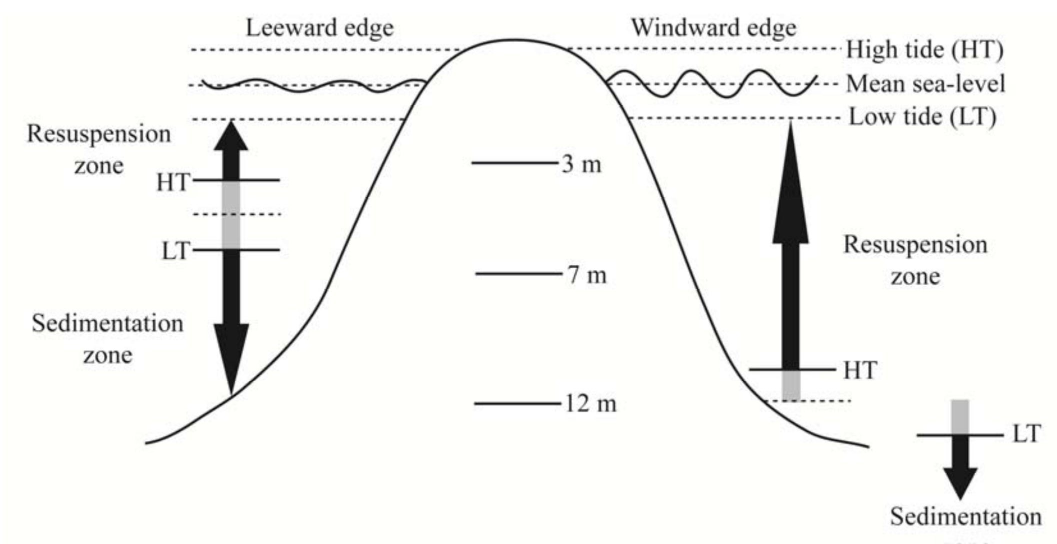

Figure 2.7: Variations in the depth of the resuspension and sedimentation zones between the windward and leeward edge, and with the tidal cycle. Adapted from Wolanski *et al.*, 2005.

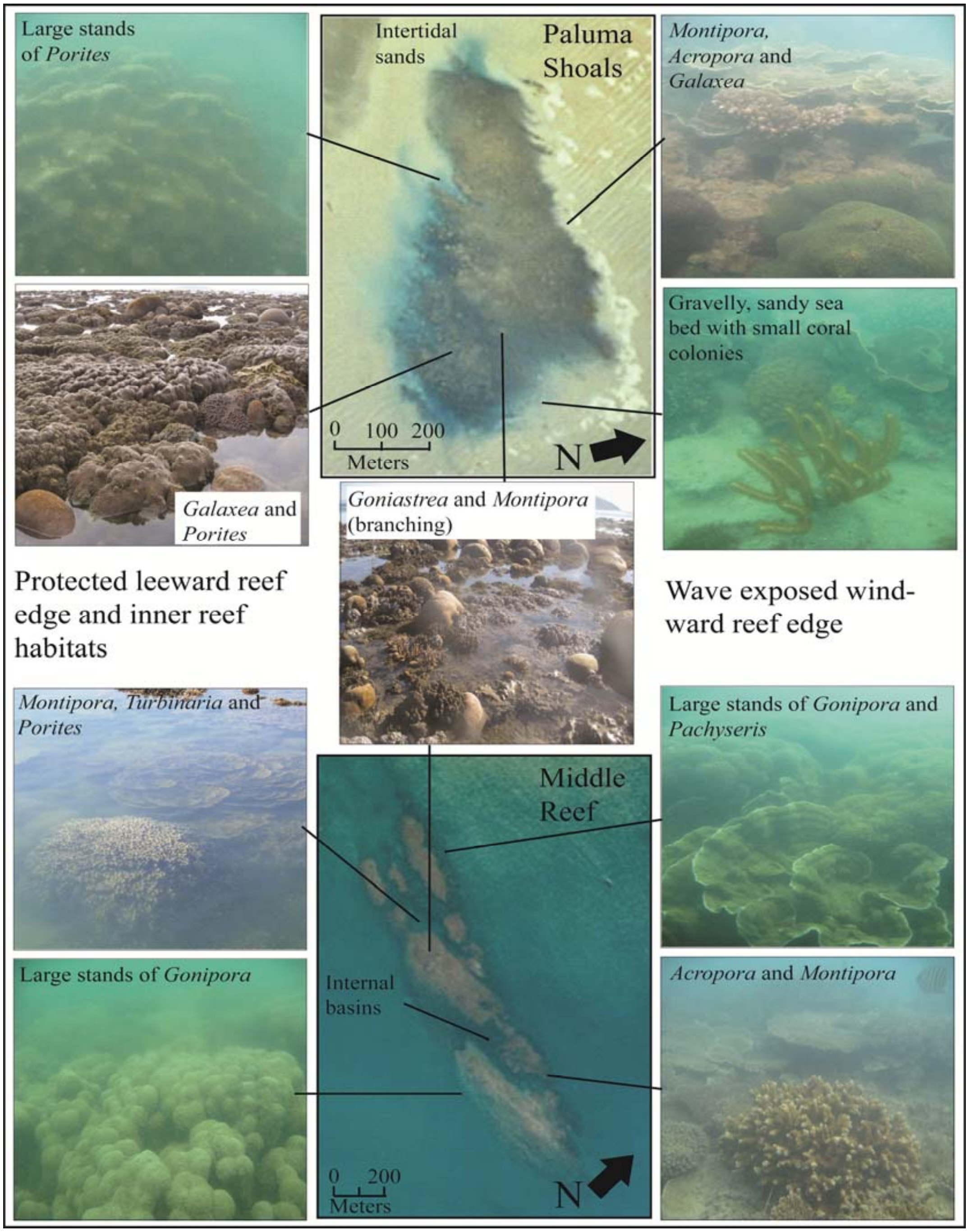

Figure 2.8: Spatial distribution of community assemblages typically observed on turbid zone reefs on the inner-shelf GBR, based on Paluma Shoals (a nearshore shoal) and Middle Reef (a nearshore patch reef). Corals resilient to high wave energy (e.g. *Acropora*) are commonly found on the reef crest; corals tolerant to high sedimentation and turbidity (e.g. *Goniopora*) are found at depth on the windward and leeward reef slopes, and inner protected slopes are characterised by corals tolerant to high sedimentation (e.g. *Turbinaria* and *Porites*).

These inner-reef habitats are composed of corals such as *Porites* and *Goniopora*, both of which are tolerant to high sedimentation and turbidity (Done, 1982; Smithers *et al.*, 2006). In contrast, exposed areas, such as the reef crest, tend to be dominated by fast-growing branching and plate corals, such as *Acropora* and *Montipora*, which are tolerant of higher wave energy conditions (Browne *et al.* 2010; Done *et al.* 2007). In general sedimentation rates are typically low on the reef flat (<1 g/m^2/day; Browne *et al.*, in review-a), which is exposed on the low spring tides and is typically dominated by corals including *Goniastrea aspera* and *Montipora digitata.* Sedimentation rates may increase towards the leeward edge as hydrodynamic exposure falls resulting in a shift in community assemblages to those often dominated by large stands of *Galaxea* (Smithers & Larcombe 2003). These coral community assemblages result in spatially variable rates of carbonate productivity which are different to clear-water reefs, and, therefore, lead to differences in reef growth and morphological development.

2.6.3 Shifting community assemblages

Assessments of coral cover and diversity based on short-term studies have concluded that over recent decades many inshore turbid reefs have experienced a community shift from diverse assemblages to those dominated by specialist coral species (DeVantier *et al.*, 1997; Done *et al.*, 2007). These shifts are interpreted as evidence of reef degradation, potentially driven by extrinsic anthropogenic pressures. However, evidence from reef cores suggests that community shifts are intrinsically driven. A total of 17 reef cores from Paluma Shoals, 15 from King Reef and 6 from Lugger Shoals, provide some of the most detailed data on species composition and growth for turbid zone reefs (Smithers and Larcombe, 2003; Perry *et al.*, 2008; Perry *et al.*, 2009; Palmer *et al.*, 2010; Roche *et al.*, 2011). These studies demonstrate that as a reef vertically aggrades within a nearshore sedimentary setting the dominant coral species (*Acropora, Goniopora, Turbinaria, Galaxea, Montipora*) change as the available accommodation space is filled and the reef approaches sea level. The influence of intrinsic and extrinsic factors on coral community assemblages has been conceptually modelled by Perry *et al.* (2008), which also illustrates the contrasting response of hypothetical coral species on turbid and clear-water reefs (Fig. 2.9). The model demonstrates that higher heterotrophic feeding capabilities may buffer coral species on turbid reefs to certain

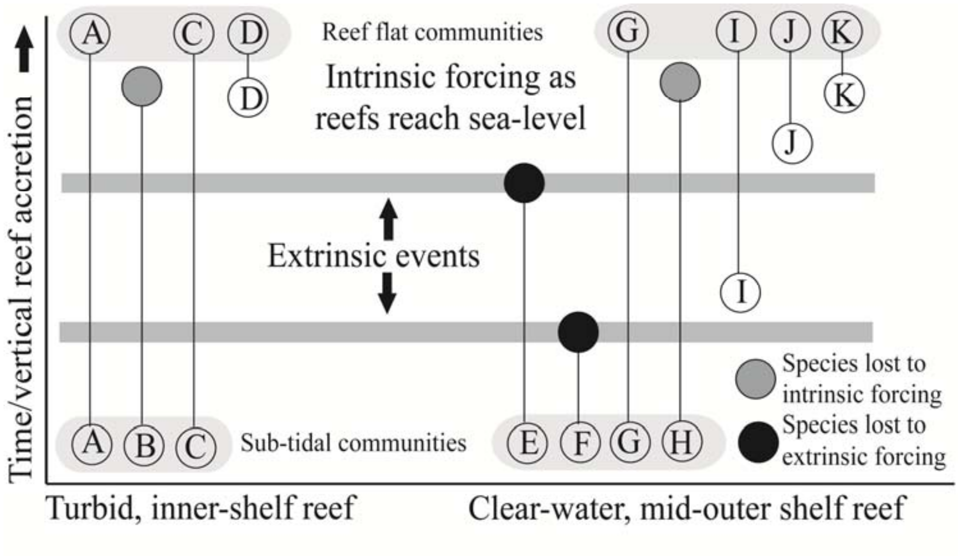

Figure 2.9: Conceptual model of changing coral communities to intrinsic and extrinsic forcing factors. The model illustrates the different responses of hypothetical coral communities between turbid and clear-water reefs, and demonstrates the importance of intrinsic forcing factors as reefs reach sea level. Adapted from Perry *et al.* 2008.

extrinsic factors such as rising SST, but on approaching sea level a shift in coral assemblages occurs to more specialised coral species that can withstand environmental conditions such as higher wave activity and exposure. These shifts are independent of the time at which the reef reaches sea level, confirming that these shifts are intrinsically driven. In contrast, on clear-water reefs, coral species are less adapted to shift between feeding strategies, and, as such, extrinsic factors may stress corals and drive mortality events, encouraging new species colonisation.

Extrinsic factors that drive community shifts may also be due to natural shifts in the sedimentary regime as opposed to anthropogenically driven shifts. For example, low coral cover and species diversity on the reef at Cahuita, Costa Rica, initially attributed to high sediment influx associated with deforestation (Cortes *et al.*, 1985), was later linked to natural processes rather than human activity (Hands *et al.*, 1993). Previous research had not considered the trend of the net shoreline recession coupled with a slow long-term rise in sea level that created an inherently dynamic shoreline and increased sediment delivery. An example of more recent reef community changes in response to natural processes was described at Low Isles turbid reefs, north of Cairns (Frank and

Jell, 2006; Frank, 2008). A fall in hard coral cover and an increase in soft corals and macro-algal cover led to the assumption that the shift was triggered by agricultural activities in local catchments (Bell and Elmetri, 1995). However, geomorphic assessments indicated that changes in the community were due to natural processes associated with the expansion of the mangroves over the reef top (Frank and Jell, 2006). Lower sedimentation and turbidity rates on the reef flat in 1991-1992 than in 1928-1929 despite an increase in the amount of land clearing on the mainland around Cairns since the late 1920's (Johnston, 1996) also dismisses human activities as responsible for community changes at Low Isles.

2.7 Modern day disturbances on reef growth

On the GBR, natural disturbances such as bleaching events, floods and cyclones are relatively common occurrences. Since the 1980's, four major and widespread bleaching events (1983, 1987, 1998, 2002) have occurred resulting in coral cover losses of >50% on some reefs (e.g. Fitzroy Island in 1998); during the 1990's five major flood plume events (1994, 1995, 1996, 1997, 1998) were recorded from the Burdekin River (Schaffelke *et al.*, 2007), the largest river discharging into the GBR lagoon; and cyclones typically visit a region approximately every 10 years (Bureau of Meteorology). Turbid zone reefs are more frequently exposed to disturbance events than offshore clear-water reefs as they are located close to river mouths (<20 km) and situated within shallow waters (<20 m) which typically experience greater fluctuations in SST. Reef recovery will depend on the nature and severity of the event as well as the level of resistance and resilience of the reef (Nystrom *et al.*, 2000).

Several long-term studies suggest that turbid zone reefs are potentially resilient not only to sedimentation and fluctuating turbidity, but also to disturbance events. Many turbid reefs have both high coral cover and diversity, characteristics considered important for reef resistance and resilience (Nystrom *et al.*, 2008), and as such, many reefs have recovered rapidly (<5 years) following disturbance events (Sweatman *et al.*, 2007; Browne *et al.*, 2010). For example, in 1986 the inshore turbid reefs off Cape Tribulation were visited by Cyclone Manu, a weak cyclonic event (<100 km.hr^{-1} winds), and in the following year a bleaching event occurred; together this reduced coral cover by 33% (Ayling and Ayling, 1999b). A survey two years later showed very rapid recovery to pre-disturbance levels in coral cover (50%; Ayling and Ayling, 1999a). Given adequate recovery periods (>5 years) between disturbance events, these events may even promote diversity and reef health. However, if the frequency and severity of disturbance events increases, reef recovery periods will be shortened, and reefs may experience high coral mortality rates, reduced species diversity (Hughes, 1989) and increased macro-algal cover (Ostrander *et al.*, 2000).

The mechanisms that enable turbid zone reefs to recover from a disturbance event may differ from clear-water reefs, and are potentially dependent on the timing of the disturbance event. Coral larvae recruitment rates are a key mechanism of reef recovery on clear-water reefs, yet on turbid reefs recruitment rates are generally low (Fabricius, 2005). Instead, the regrowth of surviving coral colonies, particularly fast-growing species such as *Acropora* and *Montipora*, is potentially critical for reef recovery (Fisk and Harriott, 1986; Ayling and Ayling, 2005). Coral growth and reef recovery will occur more rapidly if recovery occurs during a period of non-stressful environmental conditions. For example, the regeneration and regrowth of remnant *Acropora* coral tissue was observed at Keppel Islands after both the 2006 and 2008 bleaching events, and outcompeted macro-algal growth. Coral growth coincided with a seasonal die back of algae which together resulted in rapid reef recovery (Diaz-Pulido *et al.*, 2009). Fast-growing corals such as *Acropora*, which have a fragile branching structure, are more vulnerable to physical disturbance events (Madin, 2004), but their ability to grow rapidly suggests that these corals are important to the long-term survival of inshore turbid reefs (Osborne *et al.*, 2011).

Despite rapid coral growth and reef recovery, other measures are required for an appropriate assessment of reef resilience to disturbance events and vulnerability to reef degradation. Long-term data that follow reef health trajectories provide a more comprehensive assessment of reef resilience and recovery regimes. However, reef health trajectories based largely on assessments of coral cover without an assessment of why coral cover declined and the demographic processes involved (Hughes *et al.*, 2011) will only provide speculative answers to critical questions such as those regarding the mechanisms of reef resilience. While many researchers consider that declining coral cover on the GBR indicates regional reef degradation (Bellwood *et al.*, 2004; Bruno and

Selig, 2007), Sweatman *et al.* (2011) have recently argued that the GBR is less degraded from its natural, resilient state with coral cover having fallen from 28% in 1986 to 22% in 2004 due to localised rather than regional declines in coral cover. However, Hughes *et al.* (2011) argue that the GBR, in particular inshore turbid zone reefs, are losing reef resilience due to multiple disturbance events and incomplete recoveries, and calls for better monitoring of recruitment, growth and disease. Data on these additional measures are rare for inshore turbid reefs given the difficulty in conducting such observations within highly turbid settings, but will be required to assess inshore reef resilience, particularly to global threats such as bleaching which are increasing in frequency and intensity.

2.8 Projected environmental change

Inshore turbid zone reefs on the GBR are considered by some researchers to be more vulnerable than offshore clear-water reefs to global threats, particularly to bleaching events given greater fluctuations in SST inshore (Berkelmans *et al.*, 2004; Weeks *et al.*, 2008). A study by Berkelmans and Oliver (1999), conducted on 654 reefs across the GBR, found that in 1998 when SST were between 1 ^{o}C and 2 ^{o}C greater than normal for that period, 87% of inshore turbid zone reefs bleached to some extent, compared to only 28% of offshore reefs. However, bleaching inshore tends to occur at higher temperatures than on offshore reefs (Berkelmans *et al.*, 2004), partly due to a higher thermal tolerance of corals provided by its algae symbionts (Berkelmans and Van Oppen, 2006). Bleaching may also occur at higher temperatures in turbid regions due to reduced UVA and UVB penetration which together with rising SST can lead to coral bleaching. Turbid waters may, therefore, provide a degree of protection against bleaching for corals adapted to cope with high turbidity through heterotrophic feeding. However, there are still several unknowns regarding coral tolerance thresholds in warmer, turbid waters. For example, it is unknown whether the switch to more temperature tolerant algal symbionts following bleaching events (Jones *et al.*, 2008) is permanent. Furthermore, these symbionts, although providing an increased tolerance to higher temperatures, may inadvertently have a negative influence on other coral functions such as growth and carbonate accretion. Indeed a higher thermal tolerance may come at the expense of a greater reef building capacity (Bradshaw and Hardwick, 1989).

Ocean acidification is another major threat to coral reefs. Ocean pH is predicted to decrease by 0.3 to 0.4 by 2100 (IPCC, 2007) which may result in increased carbonate dissolution rates, weakened coral skeletons and lower calcification rates (Kleypas *et al.*, 1999b; Hoegh-Guldberg *et al.*, 2007; Anthony *et al.*, 2011). At this stage, there is no evidence to suggest that the direct effects of ocean acidification will be greater on turbid zone reefs than on offshore clear-water reefs. However, if calcification rates decrease globally and coral skeletons weaken in response to ocean acidification, reefs in shallow waters where the entire reef structure is exposed to wave activity may be more susceptible to breakages and reef framework destruction. As such, inshore turbid reefs are potentially more vulnerable to the effects of global warming, both rising SST and ocean acidification, but their increased vulnerability is largely the result of their setting within shallow, warmer coastal waters, as opposed to a perceived lower resilience due to naturally high sedimentation and turbidity.

2.9 Conclusions

Geological and palaeoecological data together with modern ecological data from the GBR have provided insights into the key environmental controls that influence turbid zone reef initiation and growth. Reef initiation and growth, and therefore distribution, on the inner-shelf is largely controlled by the sedimentary regime and its driving hydrodynamic forces; specifically the balance between sedimentation and sediment resuspension. Regions of active sediment resuspension and high turbidity, but low sediment deposition are more favourable for reef growth than settings where deposition rates are high, although regions of persistent and extreme turbidity will limit light penetration and reef growth. The availability of hard substrates was previously considered the primary control of coral reef initiation and distribution. However, turbid zone reefs have initiated on a range of substrates including mobile sediments, and, as such, have grown within a number of geomorphic settings. Spatial and temporal variations in the sedimentary and hydrodynamic regimes between settings have led to variable rates and modes of reef growth, and, therefore, morphological development.

Turbid zone reefs are supported by distinctive community assemblages capable of withstanding high sedimentation (>50 kg/m^2/year) and turbidity (>50 mg/L) that far exceed levels generally considered detrimental to coral growth and reef development. These assemblages differ from mid- and outer-shelf reefs, and are composed of coral species (*Porites, Goniopora, Montipora, Galaxea, Turbinaria*) which have adapted to inshore sedimentary, hydrodynamic and water quality regimes. Extensive research on coral tolerances and adaptations to increased sediment loads has provided knowledge on the mechanisms by which corals can cope with sedimentation and turbidity. Differences in coral adaptations between families and species has led to spatial variations in their distribution, with more sediment tolerant corals in protected reef regions with high sedimentation rates, and corals adapted to high turbidity in regions of high sediment resuspension. Evidence from reef cores has indicated that these coral assemblages are temporally stable over millennial timescales, which has enabled turbid zone reefs to rapidly accrete, many reaching sea level within 2,000 years. These data highlight the importance of understanding ecological adaptations and interactions with environmental controls as these influence reef morphology and growth.

Turbid zone reefs have displayed a remarkable capacity to recover quickly following natural disturbance events potentially due to an inherent resilience to their marginal environmental conditions. However, an increase in the frequency and severity of disturbance events will lead to shorter intervals between disturbances and limited reef recovery. A multidisciplinary approach is needed to address growing concerns on turbid zone reef vulnerability to increasing human pressures. Palaeoecological and geological studies provide a temporal assessment on rates of reef growth and context for current community change, and ecological studies provide data on coral-sedimentary interactions, which may in part explain how reefs have rapidly accreted in turbid zone settings. However, given the importance of terrigenous sediments to turbid zone reef occurrence, composition and growth, a critical step in the assessment of their future prospects, will be to develop an improved understanding of the sedimentary regime.

3. GEOMORPHOLOGY AND COMMUNITY STRUCTURE OF MIDDLE REEF, CENTRAL GREAT BARRIER REEF, AUSTRALIA: AN INNER-SHELF TURBID ZONE REEF SUBJECT TO EPISODIC MORTALITY EVENTS

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3.1 Abstract

Middle Reef is an inshore turbid zone reef located 4 km offshore from Townsville, Queensland, Australia. The reef consists of four current-aligned, inter-connected reef patches that have reached sea level and formed reef flats. It is regularly exposed to high turbidity (up to 50 $mg.l^{-1}$) generated by wave-driven sediment re-suspension or by episodic flood plumes. Middle Reef has a high mean hard coral cover (>39%), relatively low mean macro-algal cover (<15%), and a coral community comprising at least 81 hard coral species. Cluster analysis differentiated six benthic communities which were mapped onto the geomorphological structure of the reef to reveal a spatially patchy community mosaic that reflects hydrodynamic and sediment redistribution processes. Coral cover data collected annually from windward slope transects since 1993 show that coral cover has increased over the last ~15 years despite a history of episodic mortality events. Although episodic mortality may be interpreted as an indication of marginality, over decadal time-scales Middle Reef has recovered rapidly following mortality events and is clearly a resilient coral reef.

3.2 Introduction

The potential for anthropogenic activities to alter natural environmental conditions surrounding coral reefs and thus modify the composition, diversity, and distribution of community assemblages is well documented (Pastorok and Bilyard 1985; Hughes 1994; Greenstein *et al.* 1998; Souter and Linden 2000; Jackson *et al.* 2001; McClanahan and Maina 2003; Pandolfi *et al.* 2003). Land-based activities that reduce water quality or available light by increasing turbidity, sedimentation, pollution and nutrient delivery have negatively affected many reefs (Furnas and Mitchell 2001; Fabricius *et al.* 2005; Woolridge *et al.* 2006), but the ecological responses are ambiguous. Documented morphological and ecological changes include: reduced coral cover; changes in coral morphology; and ecological shifts in species composition and abundance (Van Woesik and Done 1997). Reefs close to heavily modified catchments are inferred to be particularly vulnerable to ecological shifts (McCook 1999); inshore 'turbid zone reefs' on the GBR characterised by low coral cover and diversity, and by high macro-algal cover have been described as 'degraded' (Jupiter *et al.* 2008). However, detailed descriptions of the morphology, community composition and community distributions over inshore turbid zone reefs are rare compared to those available for 'clear water' reefs further offshore. This paucity no doubt partly reflects the low visibility typical in these turbid environments that make data collection very difficult. However, on the inner Central GBR where turbid zone reefs have been examined, they have been found to include diverse and distinctive coral communities (De Vantier *et al.* 2006; Fabricius *et al.* 2005; Sweatman *et al.* 2007), and experience a high degree of long-term community stability (Perry *et al.* 2008b, 2009).

Here I present a detailed study of Middle Reef, an inshore turbid zone reef exposed to both naturally high (but fluctuating) turbidity conditions and to episodic flood plumes discharged from heavily modified (agriculture and urbanisation) catchments. Specifically, I: (1) present a high resolution geomorphological model constructed from detailed bathymetric surveys; (2) provide detailed data on benthic reef community composition, diversity and distribution; and (3) investigate whether particular benthic community assemblages are systematically distributed within geomorphological and bathymetric zones. This study presents detailed data of the geomorphology and community assemblages found on this reef and examines how spatial patterns of community distribution vary with geomorphological structure.

3.3 Materials and Methods

3.3.1 Study area

Middle Reef is located in Cleveland Bay, North Queensland (19°11.70′S, 146°48.70′E), approximately 4 km offshore from Townsville (Fig. 1.1). Townsville is Australia's most populous tropical city, with a sprawling urban area, and a significantly modified catchment. Cleveland Bay is shallow (maximum depths 7-15 m) and is floored by muddy sands and sandy muds (Carter *et al.* 1993). The western end of the bay includes Magnetic Island, and the Western Channel that is confined between the southern coast of Magnetic Island and the mainland. South-easterly trade winds persist during the winter months (April – November) and produce a northward-directed long-shore current and wind-waves.

Rivers discharging into Cleveland Bay also deliver freshwater and sediment. The Ross River drains a catchment of 707 km^2 (Australian Natural Resources Atlas 2009) and is the closest major river with the mouth currently almost 7 km from Middle Reef. Flood plumes from the Burdekin River, some 80 km further south, periodically influence Middle Reef. The Burdekin River is the largest river discharging into the central GBR lagoon, and regularly discharges flood plumes that extend >400 km north of the river mouth (McAllister *et al.* 2000; Devlin and Brodie 2005) and reach Middle Reef. Elevated turbidity and high suspended sediment concentrations also result from flood plumes discharged directly into Cleveland Bay, and when fine-grained sediments deposited on the seabed within the bay are resuspended by swell waves. Mean suspended sediment concentrations (SSC) of up to 200 mg l^{-1} occur in Cleveland Bay during periods of strong SE swell waves (Larcombe *et al.* 1995). Middle Reef is sheltered from strong swell waves and winds by Magnetic Island. SSCs thus tend to be lower on Middle Reef (10 – 20 mg l^{-1}) than on exposed shorelines but quickly rise to around 40 - 50 mg l^{-1} following 1 - 2 days of higher wave activity (significant wave heights >1 m) (Larcombe *et al.* 1994).

3.3.2 Reef morphology and benthic community assessments

Reef morphology was mapped using a single beam acoustic depth sounder coupled with a real time kinematic (RTK) GPS to correct for wave and boat movements. The hydrographic survey package HYPACK was used to generate a digital terrain model of the reef from the bathymetric data. Detailed morphological profiles and reef surface areas at specific depths were derived from the resulting model. Surveys to assess benthic cover were conducted during August – September 2008 by snorkelling and SCUBA at 28 sites, using 20 m GPS referenced photo transects (Hill and Wilkinson 2004). Transect locations were depth stratified (>0, -0.5, -1, -2, -3.7 m) and incorporated several reef habitats (reef flat, sheltered inner slopes, exposed outer slopes) Photographs of the substrate were taken once every metre from vertically above using a Canon camera with 23 mm lense. Camera height above the substrate was dependent on water clarity and ranged from 0.5 m to 1.5 m. Photographs were analysed using CPCe software to determine cover, composition and abundance. A stratified point count system for every 10 cm^2 allowed for variations in area sampled per photograph (Kohler and Gill 2006).

Community structure was classified using total cover of: live hard coral, soft coral, macro-algae, encrusting algae, coralline algae, sponges; substratum (pavement, coral rubble, dead intact coral, sand, silt), and 'other' (molluscs, bivalves, ascidians, anemones). To determine coral community structure, corals were classified morphologically and taxonomically to generic, and where possible, species level (Veron 2000). Statistical analysis of benthic data was conducted using the statistical package SPSS 17. Mean benthic cover for hard corals, soft corals, macro-algae and substratum were calculated for each transect using data from 20 quadrat photos. Hard coral species richness (total number of species recorded) and the Shannon-Weaver diversity index (SW H') were used to assess the diversity and spatial distribution of hard corals on the reef (Krebs 1989). One-way ANOVA's, factorial ANOVA's and multi-variant analysis using MANOVA were applied to test the hypothesis that depth was a key determinant of benthic community composition and cover. Benthic assemblage compositions (hard coral, soft coral, macro-algae, dead coral, substratum and hard coral species diversity) and distribution on Middle Reef were also examined using hierarchical cluster analysis based on percent similarity levels. Clusters were overlain onto the geomorphological model and nearest neighbour analysis conducted to generate reef zones based on community assemblages.

3.4 Results and Discussion

3.4.1 Reef morphology

Middle Reef is a linear structure, extending 1.2 km from the north-west to the south-east and 300 m across at its widest point, aligned with the dominant north-westerly (NW) currents that flow between Magnetic Island and the mainland. It rises from the shallow sea floor around 4 m below the lowest astronomical tide (LAT) level to form four discontinuous reefs flats confined by sea level (Fig. 3.1). The total three dimensional reef surface area including vertical surfaces is 366,200 m^2. Just 1.2 % of the total reef area lies between 0.7 m LAT (the highest point) and 0 m LAT, 39 % lies between 0 m and -1 m LAT, and 35 % lies between -1 m and -3 m LAT. Two prominent inner basins, 10 - 20 m wide and around 3 m deep separate the four reef flats and provide reef

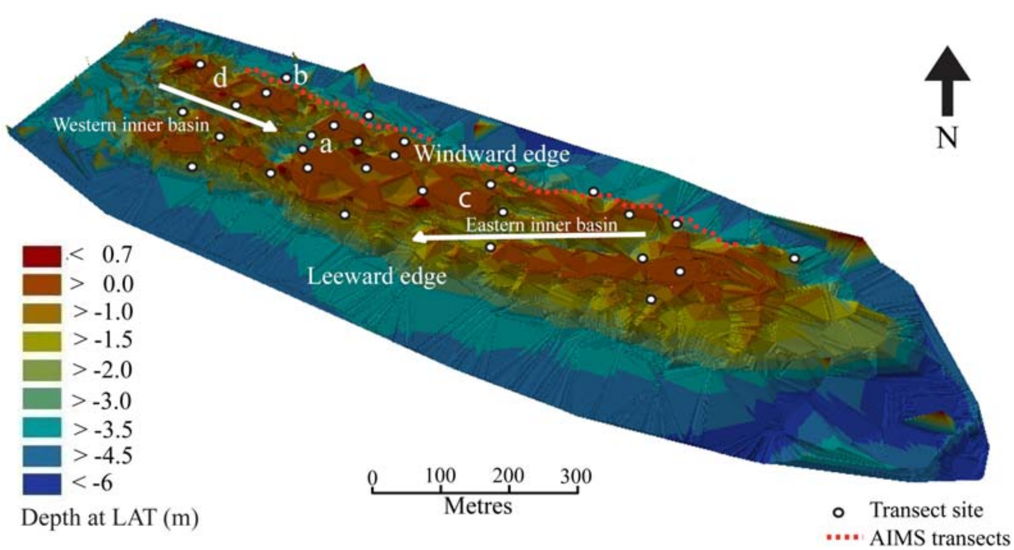

Figure 3.1: Bathymetric image of Middle Reef. Arrows indicate the two inner basins and letters a-d denote locations of Figure 3.2 photos.

slope habitat that is relatively sheltered from high wave energy. Coral cover extends to ~3.7 m below LAT on both the outer reef slopes and those descending into the interior basins, terminating where the reef meets the sediment-dominated seafloor.

3.4.2 Community assemblages

Mean live hard coral cover for Middle Reef was 39.5% (SE = 4.19); the exposed windward slope had the maximum cover of 80.5%, the leeward slope had a moderate cover of 43.5% and the central reef flat had the lowest cover of 6.6 %. Mean macro-algal cover was 14.5 % (SE = 2.54), mean soft coral cover was 5.3 % (SE = 1.64) and mean substratum cover (sand, rubble, silt) was 25.6 % (SE = 3.04). A review of data from over 1,900 reef surveys on the GBR concluded that the average live coral cover has been consistently <27% since 1986 (Bruno and Selig 2007). On this basis mean coral cover at Middle Reef is higher than that established for the wider GBR. Recent investigations from other inshore turbid zone reefs have also reported high coral cover (Perry *et al.* 2008b, 2009), challenging the perception that low live coral cover attributed to elevated turbidity and sedimentation on a number of inshore reefs (Kleypas 1996; Fabricius and McCorry 2006) is universally true.

Coral species diversity is also high. Twenty-eight hard coral genera and 81 species (26 species yet to be identified) were observed on Middle Reef, a diversity well above the 39.5 mean species richness calculated for the entire GBR (De Vantier *et al.* 2006). The average number of hard coral species recorded per transect was 8 (H' = 1.16). However, the number of species observed varied between geomorphological zones. Specifically, coral diversity was low on the reef flats (3 - 8 species, H' = 1.08), increased on the windward and leeward outer reef slopes (7 – 12 species, H' = 1.27), but was greatest on the sheltered interior slopes lining the linear basins (10 - 18 species, H' = 1.64).

Acropora and *Montipora* are the dominant genera, representing 15.9% and 10.5% respectively of the total benthic cover. *Montipora* dominates at the edge of the inner reef flat and the windward reef edge (Fig. 3.2a), and *Acropora* is most abundant on the outer and inner reef slopes (Fig.3.2b). However, both genera occur ubiquitously across the reef and are found within a range of geomorphological zones and at a range of depths. Other less common but widely distributed species include massive corals: Faviids (1.9 %), *Symphyllia* (0.5%), *Lobophyllia* (0.3 %), *Galaxea* (0.1 %), *Turbinaria* (1.1 %) and *Pachyseris* (0.3 %). The windward reef slope is dominated by stands of *Goniopora* (2 - 3 m diameter) which account for 56 % of the slope cover at ~2 - 3 m depth. The reef flat is dominated by branching *Montipora digitata* (Fig. 3.2c), interspersed with clusters of massive corals *Goniastrea aspera*, *Platygyra* and *Symphyllia*. A few *Porites* (~3 m high) are present within the sheltered, deeper regions of the inner basins. Coral genera with low abundance (>0.5%) and limited distribution include *Stylophora*, *Pocillopora*, *Pavona, Merulina, Mycedium, Echinopora* and *Hydrophora*. Soft coral cover is generally low (6.2%), but large patches of *Sarcophyton* occur on the NW exposed reef flats (Fig. 3.2d). *Sinularia* is most abundant on the exposed outer-slopes of Middle Reef with a maximum coverage of 14 % recorded on the leeward reef slope.

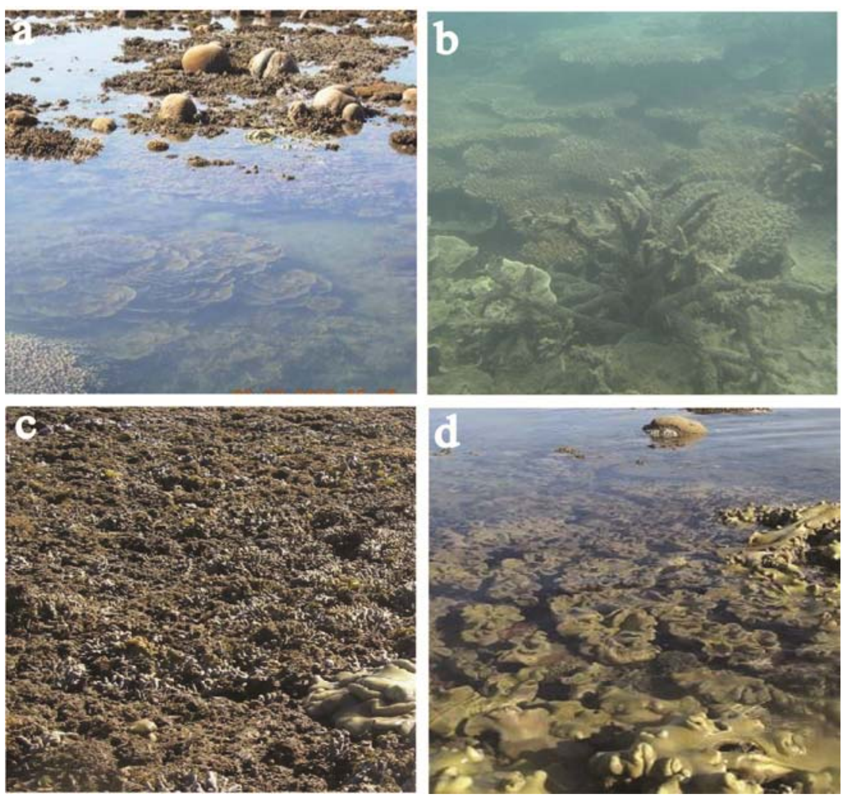

Figure 3.2: Spatial variations in coral composition at Middle Reef. (a) Coral community on the edge of the reef flat in the inner western basin dominated by plate *Montipora*, (b) Windward reef slope dominated by tabulate and branching *Acropora*, (c) Reef flat benthic community dominated by *Montipora digitata*, and (d) High abundance of *Sacrophyton* on the windward reef flat.

These data provide a detailed account of an inshore turbid-zone reef, located close to a major city and exposed to both urban and industrial contaminants. Augmented by additional long-term monitoring by the Australian Institute of Marine Science (AIMS), they provide valuable insights into temporal community dynamics. The AIMS data are derived from transects at three sites at 2 m depth on the windward slope of the reef, surveyed since 1993 using similar methods to this study. The AIMS data record a net increase in coral cover from 27% in 1993 to 45% in 2004, although the overall trend was punctuated by brief reversals in 1997, 2000 and 2002 (Sweatman, 2009). The causes of coral cover reduction in 1997 are unknown, but bleaching was identified as a potential reason in 1998 and 2000, and the Cyclone Tessi flood plume in 2002 (Sweatman *et al.* 2007). Following these disturbances the coral communities on Middle Reef recovered quickly. Our investigations indicate a current coral cover of 72.7 % on the windward slope, suggesting an increase since the AIMS 2007 survey. The higher hard coral cover may reflect an increase in Acroporids, which rose in relative abundance despite episodic 'knock backs' (Fig. 3.3).

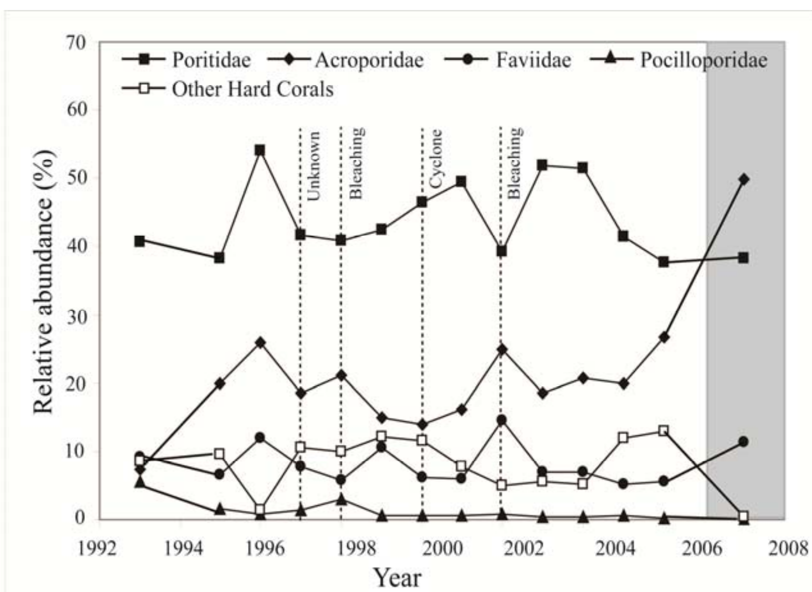

Figure 3.3: Changes in the relative abundance of the dominant hard coral families. Data collected by the long-term monitoring research team at AIMS from 1993 to 2007. Shaded area represents data collected as part of this study in 2008. Main disturbance events are highlighted.

Our data suggest that the increase in *Acropora* and *Montipora* in 2008 has overwhelmed rarer species, the relative abundance of which has fallen to <2 %. The rapid growth of Acroporids following disturbance is reported from a number of reefs across the GBR, ranging in a year from a 2 - 3 % increase in coral cover (Wakeford and Done 2008) to nearly 10 % (Ninio *et al.* 2000). In contrast, the relative cover of Poritids, Faviids and Pocilloporids has changed little over the 16 year survey period since 1993. In general, the hard coral cover measured in 2008 was much higher than that reported in 2007, and soft coral and macro-algal cover was lower, indicating a longer-term trend of increasing hard coral cover and a concomitant fall in macro-algal cover since 1993.

3.4.3 Community distribution

Light availability for symbiotic zooxanthelate photosynthesis is a primary environmental control on the development of flourishing coral reef communities, and the development of true coral reef structures, in most areas (Huston 1985; Kleypas *et al.* 1999a). Light is attenuated with depth (Graus and MacIntyre 1989), and is typically also accompanied by declining coral cover and the development of distinct depth (light)-related benthic zones (Huston 1985). However, the attenuation of light with depth is not always systematic and can be confounded by factors such as turbidity. In turbid waters light penetration can be markedly reduced within the upper 1 - 2 m, narrowing the euphotic coral growth zone (Kleypas 1996) and compressing depth-related changes in benthic community traits over narrow bathymetric intervals. Attenuation curves indicate that light penetration at Middle Reef is commonly reduced by >70% within 2 m of the surface (Fig. 3.4a) during days of 'typical' turbidity common throughout the SE trade season. In contrast, on clear water reefs, 60 - 80% reductions in light levels are only reached at approximately 10 m (Huston 1985).

The benthic cover on Middle Reef shows a transition in coral composition, abundance and morphology with depth from the reef flats down the reef slopes. To determine if these depth-related changes were significant at the reef scale, the data from all survey sites were pooled and grouped into five depth categories, each spanning an interval of 0.5 to 1 m. The mean percentage cover of hard coral, soft coral, macro-algae, dead coral and substratum were assessed with variations in depth (Fig. 3.4b). Statistical

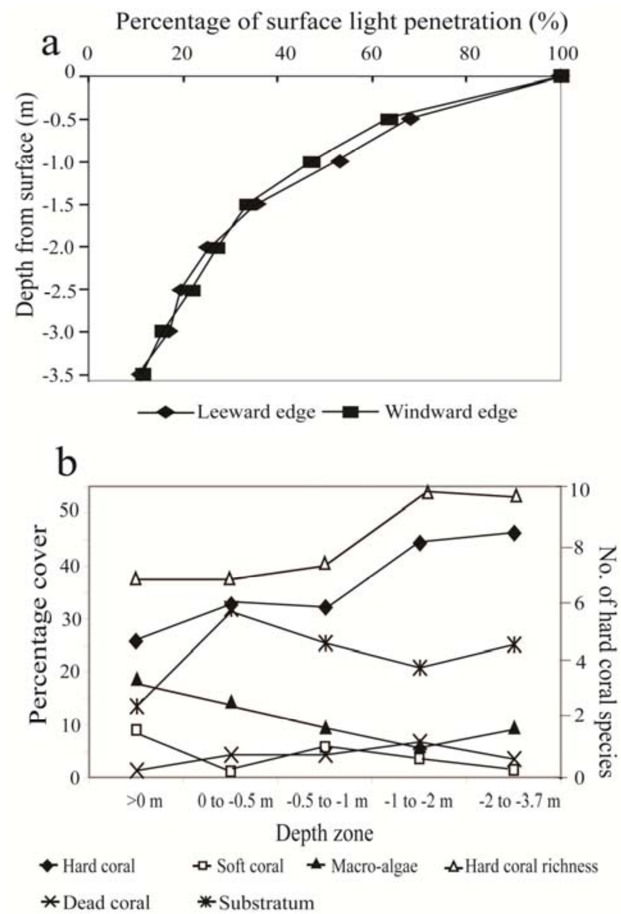

Figure 3.4: Variations in light penetration and benthic cover with depth. (a) Light penetration reductions with depth from the sea surface for the windward and leeward reef edge. (b) Change in the mean percentage cover of hard corals, soft corals, macro-algae, dead coral and substratum over five depth zones.

analysis indicated that depth-related changes were not statistically significant (P >0.05). However, hard coral cover, hard coral richness and macro-algal cover all systematically changed with depth; from the reef flat to the base of the reef slopes at 3.7 m below LAT, hard coral cover increased from 25.8 to 45.2% and the average number of species recorded increased from 7.5 to 9.7. Macro-algal cover decreased from 18.6 to 5.9% from the reef flat to 2 m below LAT, but increased to 9.6% between 2 – 3.7 m below LAT. No statistically significant relationship between depth and community assemblage character was detected at Middle Reef (in the pooled data) because the precise depth range(s) of different components varied between sites with different geomorphological characteristics. For example, the benthic cover – depth relationships on the reef slopes confining the 'interior basins' through the centre of the reef, differ from those of exposed sites on the outer reef slopes, where stronger currents are experienced at similar depths.

3.4.4 Reef zones

Middle Reef lacks the well defined benthic and geomorphological zones at the scale and level of organisation commonly seen on clear water reefs. The distinct reef crest, reef flat and back reef, with characteristic benthic communities on clear water reefs are absent. Variations in benthic communities with geomorphic zones have been investigated using community assemblages delineated by hierarchical cluster analysis. Six community types, based on hard and soft coral cover, macro-algal cover, substratum and hard coral diversity have been identified and nearest neighbour analysis of community type distribution provided a benthic zonation map (Fig. 3.5). Community type 1, characterised by high coral (71%) and low macro-algal cover (3.8%) is located on the windward reef slope and exposed sections of the eastern inner basin (Fig. 3.5: yellow regions). Community types 2 and 3, characterised by medium coral diversity (H'>1.0) and medium to high coral cover (>21%), are largely confined to the protected inner reef slopes lining the western inner basin and the semi-protected leeward reef slope that provide an array of small-scale intra-reef habitats and complex surface areas (Fig. 3.5; green regions). Community types 4 to 6, characterised by low coral cover (<20%) and high macro-algal cover (>20%), are largely confined to sheltered reef habitats where sediment cover is also usually high (Fig. 3.5; blue regions). The spatial distribution of community types has highlighted four geomorphological zones (exposed windward slope, the semi-protected leeward slope, the inner basin slopes and the reef flat). Two-way factorial ANOVA's indicated; hard coral ($p=0.083$) and macro-algal cover ($p=0.013$) varied with depth within geomorphological zones, substratum cover varied between geomorphological zones ($p=0.068$), and soft coral cover and species diversity were not significantly different between zones and depths ($p>0.1$). These analyses show that the geomorphic and hydrodynamic setting has a strong influence on benthic cover and composition.

This study shows that inshore turbid reefs support ecologically and morphologically diverse reef communities. Mean hard coral cover exceeds the mean for the wider GBR,

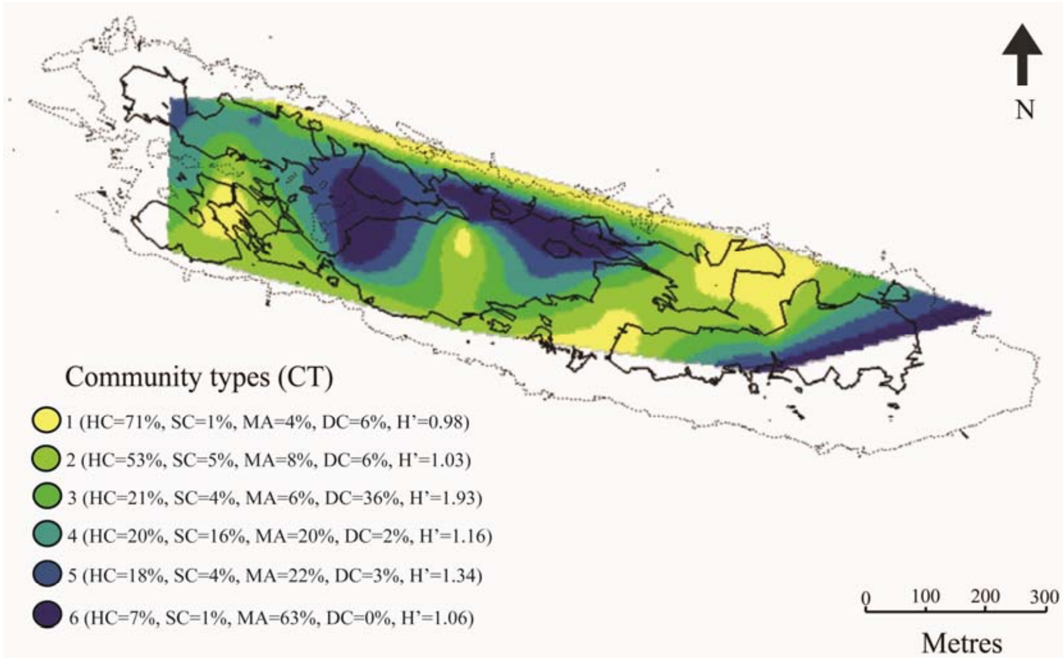

Figure 3.5: Community type distribution over Middle Reef. Coloured circles denote community types at transect sites that have been extrapolated using nearest neighbour analysis to generate reef ecological zones. Blue regions indicate low hard coral cover and high macro-algal cover, green regions indicate high hard coral diversity and moderate hard coral cover, and yellow regions indicate high hard coral and low macro-algal cover (HC = hard coral, SC = soft coral, MA = macro-algae, DC = dead coral, H' = hard coral diversity).

and species diversity can be described as 'moderate' as 81 species have been recorded (De Vantier *et al.* 2006). However, hard coral cover, species composition and diversity are highly variable within the different morphological zones. The result is a robust and spatially diverse contemporary benthic community, potentially influenced by variations in sediment characteristics, water flow and the complex reef morphology. Middle Reef has accreted to form a complex structure, despite episodic high turbidity conditions and disturbance events such as coral bleaching and cyclone-related flooding. These data suggest a high degree of coral community resilience to natural disturbance events within terrigenous sediment influenced, high turbidity inner-shelf environments. Aside from natural high and varied sedimentation and turbidity, Middle Reef lies within an urban catchment area and is exposed to a wide range of human influences and contaminants that may stress the benthic community. Despite both natural and anthropogenic stressors, Middle Reef has displayed a remarkable capacity to recover rapidly from disturbance events, and coral cover has increased markedly over the last ~15 years (to 2008). The ability to recover from such disturbances and chronic changes related to industrial, pastoral and urban development of nearby coastal catchments suggests a high degree of resilience. Adaptation and/or acclimatisation to naturally high and fluctuating turbidity may equip these inshore reef communities with an inherent resilience to both natural and anthropogenic disturbance (Meesters *et al.* 2002), and may be cause for some optimism regarding their long-term future.

4. CARBONATE SEDIMENT SIGNATURES ON INSHORE REEFS EXPOSED TO HIGH TERRIGENOUS SEDIMENT DELIVERY ON THE CENTRAL GREAT BARRIER REEF

To be submitted to Sedimentology (September 2011)

4.1 Abstract

Reefal carbonate sediments are often considered to be geo-indicators of spatial variations in benthic cover as they are produced by organisms that typically grow within distinct geomorphological zones. However, the addition of terrigenous sediments on inshore turbid reefs on the Great Barrier Reef (GBR) may influence carbonate sediment facies development and it's relationship with biological zonation. This study describes grain size, texture and carbonate composition at two inshore turbid reefs on the central GBR; Middle Reef and Paluma Shoals. Middle Reef is a nearshore patch reef situated within a semi-enclosed bay, protected from strong winds and swell, and Paluma Shoals is shore-attached, situated in an exposed position within a large open bay. Sediments ranged from slightly gravelly sands to sandy muds, and contained on average between 50-60% carbonate. Carbonate sediments were dominated by coral (30%) and mollusc fragments (25%), and contained <10% crustose coralline algae (CCA), alcyonian spicules, foraminiferans, annelids and crustaceans. The mean sediment composition reflected benthic cover (hard coral, soft coral, CCA cover) suggesting that these sediments provided an accurate record of carbonate productivity despite high terrigenous sediment inputs. Sediments were classified into facies (texture and composition) and were mapped onto digital terrain models to assess distribution with reef morphology and benthic cover. At both reefs, the mean particle size and level of sorting decreased from the exposed windward edge to the sheltered leeward edge reflecting spatial variations in wave energy. Spatial variations in sediment composition were related to benthic cover at Middle Reef but not at Paluma Shoals due to higher wave resuspension and redistribution of sediments. In summary, similar sediment facies composition at both reefs suggests that these sediments provide a reef signature for inshore turbid reefs, as well as reflecting reef carbonate productivity, but sediment distribution over the reef is dependent on the hydrodynamic regime.

4.2 Introduction

Inshore turbid reefs on the central Great Barrier Reef (GBR) are composed of mixed carbonate and terrigenous sediments (Woolfe & Larcombe, 1998; Larcombe *et al.*, 2001; Perry & Smithers, 2006). Carbonate sediments include the skeletal remains of both whole organisms and organisms broken down through mechanical and biological erosive processes, and terrigenous sediments are imported on to the reef. Sources of terrigenous sediments include land and river runoff, as well as sediments resuspended from the muddy sediment body, termed the inshore sediment prism (ISP), which extends from the shoreline to approximately 15 m depth along most of the GBR (Johnson & Carter, 1987). The rate of sediment supply is, therefore, dependent on autochthonous (*in situ*) sediment production which is determined by the abundance of calcifying organisms and the rate of breakdown (Scoffin, 1992), and allochthonous (imported) sediment input which is dependent on sediment transport processes. The spatial distribution of sediments over reefs is controlled by redistribution processes driven by wave and current energy (Scoffin, 1992), biogenic reworking of sediments (Perry, 1996), and for carbonate sediments, the spatial distribution of calcifying organisms and the rate of production. If redistribution processes and biogenic reworking are limited, carbonate sediment composition will be closely related to benthic cover and reflect reef productivity (Perry, 1996; Hewins & Perry, 2006). Sediments that remain *in situ* are eventually incorporated into the reef framework, filling in voids and cavities, and therefore, aid reef growth and development (Hubbard *et al.*, 1990; Woolfe & Larcombe, 1999; Mallela & Perry, 2007).

The delivery of terrigenous sediments to inshore reefs on the GBR is considered to have detrimental influences on coral cover and diversity (Fabricius & De'ath, 2001; Fabricius, 2005; Weber *et al.*, 2006). High volumes of terrigenous sediments if deposited on the reef may smother and bury reef corals (Loya, 1976), and/or stress corals thereby increasing the prevalence of tissue infections (Nugues & Callum, 2003; Fabricius, 2005; Fabricius *et al.*, 2005), whereas resuspended sediments reduce light availability for coral photosynthesis (Rogers, 1990; Wolanski & De'ath, 2005). Corals are typically the main carbonate producer on coral reefs and, therefore, reductions in coral cover due to terrigenous sediments would have longer-term implications for inshore turbid reef growth and development. However, palaeoecological reconstructions using reef cores indicate that terrigenous sediments are a volumetrically important component of inshore reef structure and that many of these reefs have rapidly accreted despite high terrigenous sediment inputs (Perry & Smithers, 2006; Smithers *et al.*, 2006; Palmer *et al.*, 2010).

Previous qualitative studies have concluded that terrigenous sediments do not control carbonate production, but rather the nature of sediment accumulation and reef growth (Woolfe & Larcombe, 1998, 1999). However, only a few studies have characterised sediments on inshore turbid reefs to assess the influence of terrigenous sediments on contemporary carbonate sediment production and accumulation. As such, there is limited knowledge on the relationship between the distribution of reef biota, and carbonate sediment composition and distribution on reefs influenced by terrigenous sediments. This paucity may partly reflect the difficult environmental conditions such as low visibility and hazardous marine life which make field work technically difficult and dangerous in these settings. This study provides data on sediment composition and examines sediment facies distribution in relation to reef geomorphology and benthic cover at two inshore turbid zone reefs; Middle Reef (19^{o}11.70′S, 146^{o}48.70′E) and Paluma Shoals (19^{0}7.08’S, 146^{0}33.23’E). The objectives were to: (1) characterise sediment texture and composition, and identify sediment facies, (2) map sediment textural and compositional facies over a reef bathymetric model and, (3) discuss sediment composition and distribution in relation to benthic cover. This research provides a detailed analysis of spatial variations in sediment composition, and considers the key driving factors that control carbonate sediment accumulation on reefs exposed to high terrigenous sediment loads.

4.3 Materials and Methods

4.3.1 Study area

Middle Reef and Paluma Shoals are situated on the inner shelf of the central GBR. Middle Reef is located within Cleveland Bay, North Queensland and lies approximately

4 km offshore from Townsville and 2 km west (W) of the Platypus channel, a dredged shipping channel that allows large ships access to Townsville Port (Fig. 1.1). Paluma Shoals lies approximately 30 km north (N) of Townsville, in central Halifax Bay (Fig. 1.1). Both Cleveland Bay and Halifax Bay are shallow (<20 m) and are dominated by mixed-siliclastic-carbonate sediments (Belperio, 1988) with a terrigenous component of mainly quartoze medium-grained sand, silt and clay (Maxwell & Swinchatt, 1970). The largest source of terrigenous sediment to the central GBR is the Burdekin River, situated approximately 80 km south (S) of Cleveland Bay, whose flood plumes extend up to 500 km N following heavy rains (Lewis *et al.*, 2006). On the central GBR, >80% of the annual rainfall typically occurs during the summer months (December to February) with February experiencing the highest amount of rainfall (296.6 mm), and September the lowest (10.1 mm). Additional sources of sediment to Cleveland and Halifax Bay include the Ross River, Bohle River and the Black River which have a combined sediment yield of 0.13-0.55 Mt (Fig. 1.1; Neil *et al.*, 2002).

The tidal cycle is semi-diurnal with a spring tide maximum range of 3.8 m. Waves are the main agent of sediment resuspension on the inshore GBR, and wind-driven currents transport suspended sediments northwards (Larcombe *et al.*, 1995; Lou & Ridd, 1996; Larcombe & Woolfe, 1999a). In Cleveland Bay, mean suspended sediment concentrations (SSC) of up to 100 NTU occur during periods of strong SE swell (Larcombe *et al.*, 1995), but SSC's at Middle Reef tend to be lower (<10 Nephelometer Turbidity Units (NTU)) as Magnetic Island protects Middle Reef from high energy winds and waves (Larcombe *et al.*, 1994). In contrast, Halifax Bay is open and Paluma Shoals is exposed to larger wind-driven waves generated over a larger fetch. Peak turbidity readings >150 NTU have been recorded, with around 40 days per year exceeding 40 NTU (Larcombe *et al.*, 2001).

4.3.2 Study sites

Middle Reef

Middle Reef is a linear patch reef (1.2 km x 0.3 km) aligned with the dominant north-westerly (NW) currents that flow between Magnetic Island and the mainland (Fig. 4.1a). Two prominent linear basins, (10 - 20 m wide) around 3 m deep, separate four reef flats and provide reef slope habitat that is sheltered from high wave energy on the windward edge (Fig. 4.2a). Coral cover extends to ~3.7 m below LAT on both the outer and inner reef slopes, and coral cover is dominated by *Acropora* and *Montipora* (Browne *et al.*, 2010).

Paluma Shoals

Paluma Shoals consists of a larger southern shoal (500 m x 820 m) and smaller northern shoal complex, both of which extend down to a depth of ~3.5 m at LAT on the windward slope. This study is based on the southern shoal which is a connected to the mainland at its NW end via inter-tidal sand flats (Fig. 4.1b). The tops of massive corals grow up to 0.85 m LAT and the reef flat is fully emergent at 0.5 m LAT. The western reef flat has a relatively even reef surface where as the eastern reef flat surface is dominated by large microatolls and massive corals interspersed with pools (> -0.5 m) lined with fine sediments (Fig. 4.2b). A number of palaeoecological and contemporary benthic community studies have been conducted on Paluma Shoals (Woolfe & Larcombe, 1999; Larcombe *et al.*, 2001; Smithers & Larcombe, 2003; Palmer *et al.*, 2010). Coral assemblages are dominated by the sediment tolerant species including *Galaxea fascicularis, Porites* and *Goniastrea.*

4.3.3 Reef morphology and benthic assessments

Reef morphology was mapped using a single beam acoustic depth sounder coupled with a real time kinematic (RTK) GPS to correct for wave and boat movements. The hydrographic survey package HYPACK was used to produce a digital terrain model of

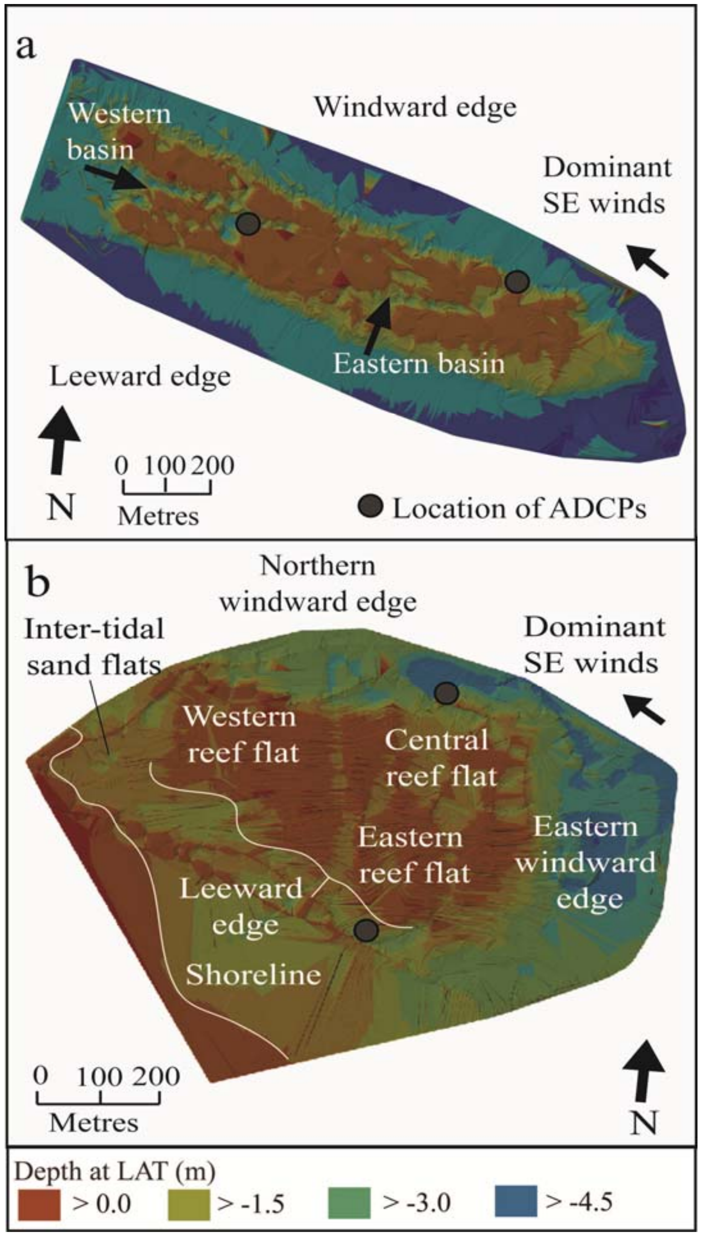

Figure 4.1: Bathymetric images of (a) Middle Reef and (b) Paluma Shoals. Location of the ADCPs is indicated on each reef.

the reef from the bathymetric data. Field surveys to assess benthic cover were conducted during August – September 2008 on snorkel and SCUBA using 20 m GPS referenced photo transects (Hill & Wilkinson 2004). A total of 30 were conducted at Middle Reef and 29 transects at Paluma Shoals using methods as described in section 3.3.2.

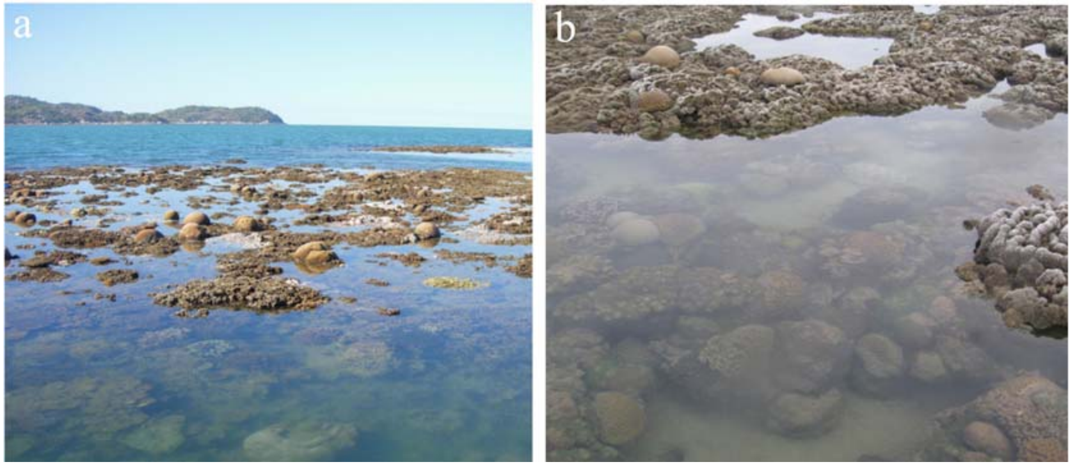

Figure 4.2: Coral community assemblages within (a) sheltered regions within the western basin at Middle Reef which contrasts to the wave exposed windward reef edge in the background, and (b) sediment lined pools (-0.5 m) on the eastern leeward reef flat at Paluma Shoals.

4.3.4 Wave measurements

Wave measurements were taken every 20 minutes during the survey period using Nortek 2 MHz Acoustic Doppler Current Profilers (ADCP). Measurements included the mean, minimum and maximum significant wave height (H_{sig}), and the mean wave direction. The sampling frequency was 2 Hz and the burst length was 512 seconds. ADCPs were mounted on a square aluminium frame approximately 30 cm off the sea floor weighted down with a 20 kg weight to ensure instrument stability, and were deployed at an exposed and sheltered site at each reef in April/May 2009 (Fig. 4.1). Wave data were analysed using STORM, a data management, processing and viewing tool for Nortek instruments.

4.3.5 Sediment sampling

Surface sediment samples were collected by hand in conjunction with benthic surveys described above. At each sampling location approximately 100 g of sediment was collected and stored in a sealable plastic bag. Samples were soaked in 5% domestic bleach solution over night and oven dried at 55^0C for 24-48 hrs. Dried samples were then quartered using a sediment splitter (~25 g): one sub-sample was used to assess carbonate content; one sub-sample was used to determine particle size distribution; one sub-sample was used to examine sediment grain composition; and one sub-sample was stored as reference material.

4.3.6 Carbonate analysis of sediment samples

Carbonate content was determined using approximately 5-7 g of the sub-sample. The sub-sample was weighed accurately to 0.001g before 10% HCl solution was added to dissolve the calcium carbonate. After 24 hrs the non-carbonate residue was filtered through a pre-weighed 90 µm filter paper using a suction filter and oven dried at 55^0C for ~4 hrs. Once the filter paper was dry, the paper and the sample were reweighed. Carbonate content was calculated by subtracting the post-dissolved sample from the pre-dissolved sample.

4.3.7 Particle size analysis

Particle size was determined using a Malvern Mastersizer-X laser particle sizer for fine sediments and a Rapid Sediment Analyser (RSA) settling tube for the coarser sediment fraction. The Malvern Mastersizer X is capable of assessing particle sizes accurately to 0.02 µm, but can only be used for fine sediments <500 µm (Woolfe and Michibayashi 1995). Prior to particle size analysis, the sediment sample was weighed and wet sieved into a fine and coarse fraction using a 420 µm sieve to ensure that the fine sediment fraction was well within the Mastersizer limitations. The coarse fraction (> 420 µm) was oven dried and reweighed to determine its proportion by weight of the original sample. Sub-samples of the coarse (10-15 g) and wet fine fraction (10-20 ml) were then used to determined the particle size distributions of the larger and less than 420 µm fractions respectively, before the data were combined using Gradistat software to produce a particle size distribution curve for the total sample. The programme was also used to determine a range of statistics including the mean, mode, skewness and kurtosis of the sediments (Blott & Pye, 2001).

4.3.8 Sediment grain identification

The skeletal origin of sediment grains were identified using a binocular microscope (Olympus SZ40, magnification 40X). A total of 24 and 26 samples were analysed for Middle Reef and Paluma Shoals respectively. The sub-sample was dry sieved into five sieve fractions (>2, 1.2-2, 0.85-1.2, 0.4-0.85, <0.4 mm) and composition was assessed by identifying 100 sediment grains for each size class. Carbonate grains <0.2 mm were not examined due to associated difficulties in identifying grain type. If fewer than 100 grains were present in a sub-sample, percentage abundances were amended accordingly. Grains were classified into the following categories: hard coral, crustose coralline algae (CCA), *Halimeda* spp., bivalves, gastropods, unidentified molluscs, crustacean debris, foraminifera, echinoid spines, annelid worms and tube casings, alcyonians, bryozoans, non-carbonate material and unidentified grains. Sediment composition was expressed as the relative percentage abundance of the total sample ('sieve method'; Martin & Liddell, 1988) and for each of the sieved sub-samples.

4.3.9 Data analysis

Spatial variations in sediments were examined in the statistical package SPSS 17 using both particle size data and composition. The mean particle size, the particle size distribution and dominant modes were use to describe sediments and classify them into textural groups (sand, muddy sand, gravelly muddy sand, slightly gravelly sand, sandy mud and slightly gravelly sandy mud). The sediment skeletal composition was described using the mean percentage abundance of the grain constituents for the whole sample and also for the five size fractions to assess how sediment composition varied with grain size. Spearman's rank correlation coefficient tests were conducted to determine if the sediment size characteristics and composition were related to reef morphology (windward to leeward edge) and depth.

Six benthic assemblage clusters (hard coral, soft coral, macro-algae, dead coral, substratum and coral species diversity) were delineated as described in Browne *et al*. (2010). Clusters were laid onto bathymetric models of Middle Reef and Paluma Shoals, and nearest neighbour analyses were conducted to generate six reef zones of similar benthic cover. Spearman's rank correlation coefficient tests were conducted to determine if sediment skeletal components were significantly correlated to benthic cover. The thirteen skeletal components (unidentified grains were excluded) were reduced to five factors using factor reduction analysis. These five extracted factors were used to classify sediments into compositional groups using the k-means clustering technique. Sediment facies were delineated using both textural and sediment compositional groups, and their distribution was described in relation to both reef morphology and benthic cover.

4.4 Results

4.4.1 Reef morphology and benthic cover

Middle Reef and the Paluma Shoals are small (<1 km^2), shallow inshore turbid reefs with very different morphologies. Middle Reef is a current-aligned reef composed of a discontinuous reef flat and two deep (<4 m) linear basins (Fig. 4.1a) whereas Paluma Shoals is a shore-attached reef with a continuous reef flat (Fig. 4.1b). Wave heights were higher at the exposed eastern windward reef edge at Middle Reef (H_{sig}=0.21) and at Paluma Shoals (H_{sig}=0.48 m), decreasing westwards over both reefs (H_{sig}=0.17 and 0.38 m; Table 4.1), and waves typically approached from the north-east (NE) to south-east (SE).

Table 4.1: Wave characteristics at an exposed and sheltered site on Middle Reef and Paluma Shoals.

Reef	Site	Significant wave height (m) Mean	Min	Max	Wave direction
Middle Reef	**Eastern**	0.21	0.06	1.74	E to SE
	Western	0.17	0.05	0.64	E to SE
Paluma Shoals	**Windward**	0.48	0.09	1.27	NE to E
	Leeward	0.38	0.06	1.09	NE to E

Live hard coral cover was 39.5% (SE = 4.19) at Middle Reef and 30% (SE = 3.94) at Paluma Shoals. Soft coral cover was consistently low on both reefs (5%), macro-algal cover varied over the reef (Middle Reef = 14%, Paluma Shoals = 10%) with highest cover observed on the central reef flats (>20%), and CCA cover (Middle Reef = 2%, Paluma Shoals = 3%) was greatest along the exposed windward reef edge (<7%). Coral diversity was greater at Middle Reef than at Paluma Shoals, with >80 species identified and >60 at Paluma Shoals. At Middle Reef the dominant corals, *Acropora* (15.9%) and *Montipora* (10.5%), were most abundant on the windward reef edge (>30%). The reef flat was dominated by the branching coral *Montipora digitata* (<14%), interspersed with clusters of massive corals (<10%): *Goniastrea aspera, Platygyra* and *Symphyllia*. At Paluma Shoals, *Galaxea* was the dominant coral (13.1%) and was most abundant on the eastern leeward reef flat (>70%). Also common on the reef flat were *Goniastrea* (<10%), *Porites* (<10%) and *Platygyra* (<3%), whereas *Goniopora* (<50%), *Montipora* (<20%) and *Turbinaria* (<15%) were more abundant on the reef slopes.

4.4.2 Sediment texture

Surficial sediments were dominated by poorly to very poorly sorted sediments with polymodal size distributions (Table 4.2). Textural classes are described below using percentage weights for gravel, sand and silt together with statistical descriptors of grain size distribution. The grain size distribution of a representative sample from each textural class determined for each reef is plotted in Figure 4.3.

Slightly gravelly sand

Sediments were moderately to poorly sorted (1.4 to 2.4 σ_G) and consisted of approximately 95% sand. The grain size distributions were finely to very finely skewed (<-0.14 Sk_G) and ranged from leptokurtic to very leptokurtic (1.9 K_G). At Middle Reef, the mean grain size was 540 µm and distribution of particles (D10-D90) ranged from 410-740 µm (average = 630 µm). Sediments were mostly bimodal with modes at 400 to 600 µm (medium sand) and 1000-1200 µm (very coarse sand; Fig. 4.3a). At Paluma

Table 4.2: Textural groups for Middle Reef and Paluma Shoals.

Reef	Textural group	n	Mean (µm)	D10-D90	Skewness (Sk_G)	Kurtosis (K_G)	Sorting ($σ_G$)	Sample type	Mode 1 (µm)	Mode 2 (µm)	Mode 3 (µm)	%age gravel	%age sand	%age silt	% $CaCO_3$
Middle Reef	Slightly gravelly sand	5	534.0	628.9	-0.30	1.94	2.4	Bimodal	400 to 600	1000 to 1200		2.0	94.6	3.4	68.0
	Slightly gravelly muddy sand	9	181.5	678.6	-0.44	1.27	4.5	Polymodal	7 to 20	100 to 250	450 to 700	1.9	73.4	24.6	69.0
	Muddy sand (a)	5	269.8	661.8	-0.62	1.73	3.2	Polymodal	100 to 200	400 to 700		0.0	85.7	14.3	74.3
	Muddy sand (b)	6	114.3	494.3	-0.43	1.00	4.6	Polymodal	5 to 20	400 to 700		0.0	69.8	30.2	57.5
	Slightly gravelly sandy mud	3	38.2	391.6	0.03	0.87	5.5	Polymodal	5 to 10	50 to 70	500 to 700	1.4	34.7	63.9	37.3
	Sandy mud	2	24.3	137.8	0.00	0.83	4.1	Polymodal	5 to 10	10 to 20	50 to 70	0.0	27.8	72.1	42.7
Average		30	194.5	498.8	-0.29	1.27						0.9	64.3	34.8	58.1
Paluma Shoals	Slightly gravelly sand	8	609.5	931.5	-0.14	1.93	1.9	Polymodal	400 to 700	1200 to 1600		1.8	95.7	2.5	61.3
	Sand	2	486.7	559.7	-0.30	1.84	1.7	Unimodal	700 to 900			0.0	96.4	3.6	36.0
	Slightly gravelly muddy sand	7	207.7	794.7	-0.51	1.17	4.8	Polymodal	7 to 20	100 to 250	450 to 700	1.6	73.0	25.5	58.3
	Muddy sand (a)	3	250.9	507.3	-0.46	2.56	2.7	Polymodal	100 to 200	400 to 700		0.0	85.9	14.1	48.1
	Muddy sand (b)	4	133.2	782.6	-0.62	0.84	5.5	Polymodal	5 to 50	200 to 700		0.0	69.6	30.4	51.2
	Sandy mud	5	31.6	287.0	0.07	0.87	5.0	Polymodal	5 to 10	10 to 20	50 to 70	0.0	32.9	67.1	61.4
Average		29	286.6	643.8	-0.33	1.53						0.6	75.6	23.8	52.7

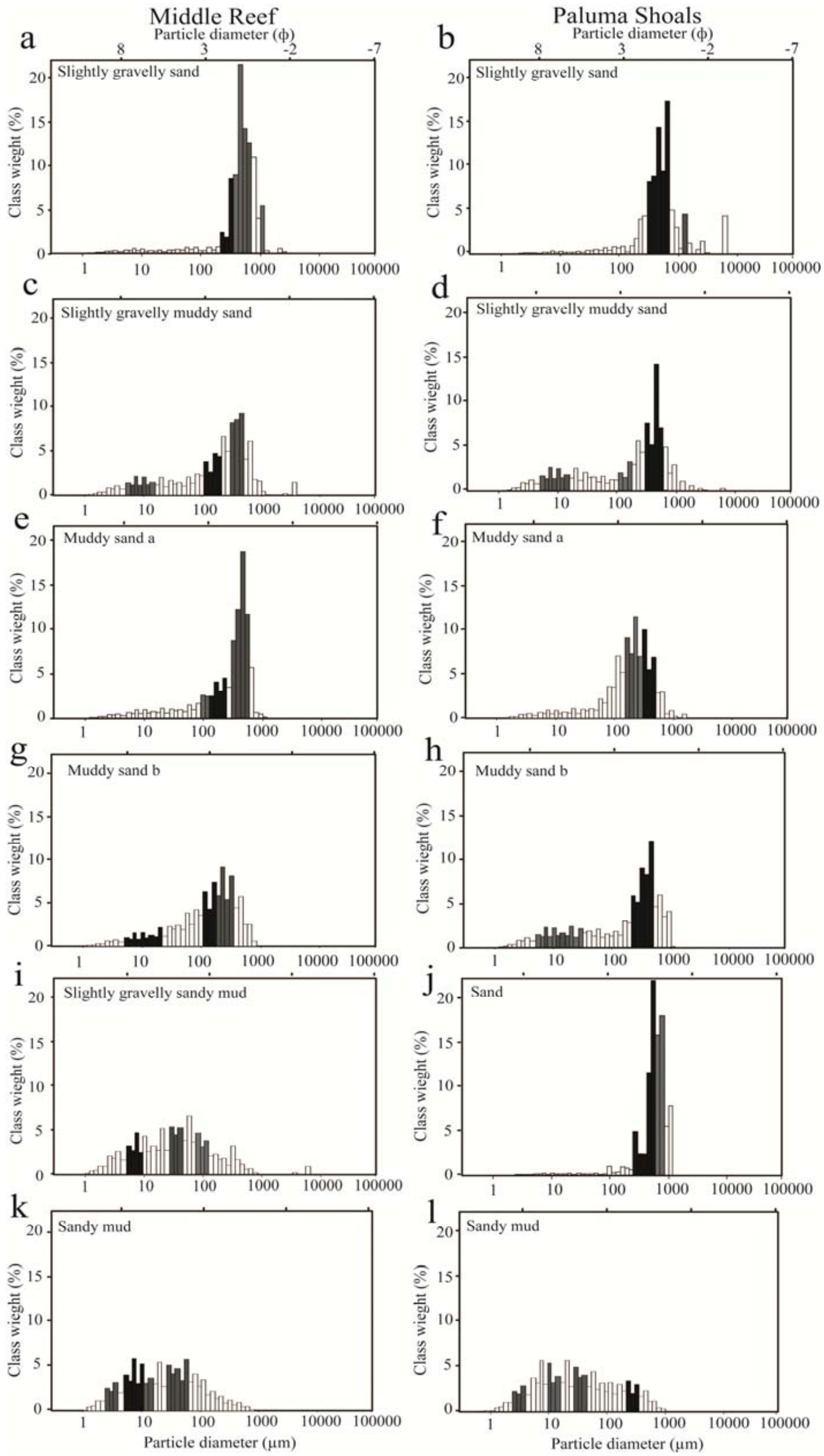

Figure 4.3: Textural group particle size distributions. Black bars denote sediment mode consistently found in all samples, and grey bars denote the dominate modes.

Shoals, mean grain size was greater (610 µm) than at Middle Reef and the distribution of particles ranged from 570 to 1500 µm. The particle size distribution was polymodal with dominant modes at 400 to 700 µm (coarse sand) and 1200-1600 µm (very coarse sand; Fig.4.3b).

Slightly gravelly muddy sand.

These sediments were sands (73%), but included a large silt fraction (25%). The grain size distributions were typically very finely skewed (<-0.3 Sk_G) but ranged from mesokurtic (0.9 K_G) to very leptokurtic (2.8 K_G), and were poorly (2.5 σ_G) to very poorly sorted (7.1 σ_G). The majority of the samples were polymodal with dominant modes at 7 to 20 µm (very fine to fine silt), 100-250 µm (fine sand) and 500 to 700 µm (coarse sand; Fig. 4.3c & d). At Middle Reef, the mean grain size was 181 µm and the distribution of particles ranged from 560 to 1100 µm. At Paluma Shoals, the mean grain size was greater (208 µm) and the distribution of particles was widely spread ranging from 570 to 1400 µm.

Muddy sand

These sediments had a large sand fraction (>70%), between 14 to 30% silt content and 0% gravel content. Sorting ranged from poor (2.6 σ_G) to very poorly sorted (6.1 σ_G) and the grain size distribution curves were typically very finely skewed (>-0.3 Sk_G). Muddy sands were separated into two subclasses; muddy sand (a) with a lower silt content (~14%) and muddy sand (b) with a higher silt content (30%). At both reefs muddy sand (a) was very leptokurtic (>1.73 K_G) and had a mean grain size of 250 to 270 µm, and muddy sands (b) were mesokurtic (<1.0 K_G) and had a mean grain size of approximately 110 µm (Fig. 4.3e to h). Both subclasses were polymodal; the dominant modes of muddy sands (a) were 100 to 200 µm (fine sand) and 400 to 700 µm (medium to coarse sand), and the dominant modes of muddy sands (b) were 5 to 20 µm (very fine to fine silts) as well as 400 to 700 µm (Fig. 4.3 & h).

Slightly gravelly sandy mud

These sediments were collected from Middle Reef and were composed principally of silt (64%), but also had a high sand content (34%) and low gravel content (1 to 2%). The grain size distribution was symmetrical (0.03 Sk_G) and platykurtic (0.87 K_G), and sediments were very poorly sorted (5.4 σ_G). Sediments were polymodal with dominant modes at 5 to 10 µm (very fine silt), 50 to 70 µm (coarse silt) and 100 to 200 µm (fine sand; Fig. 4.3i).

Sand

These sediments had the largest sand fraction (>95%) and no gravel, and were collected from Paluma Shoals. Sediments were moderate to moderately well sorted (1.67 σ_G) and the grain size distribution was very finely skewed (-0.3 Sk_G) and very leptokurtic (1.84 K_G). The mean grain size was 487 µm and the particle size distribution ranged from 465 to 655 µm. Sediments were unimodal with the dominant mode between 700 to 900 µm (coarse sand; Figure 4.3j).

Sandy mud

These sediments were dominated by silt (>64%) and gravel content was 0%. All samples collected were very poorly sorted (>4 σ_G) with a symmetrical (-0.04 to 0.07 Sk_G) and platykurtic (<0.9 K_G) grain size distribution. The mean grain size was 24 µm at Middle Reef and 32 µm at Paluma Shoals. Sediments were polymodal with dominant modes at 5 to 10 µm (very fine silt), 10 to 20 µm (fine silt) and 50 to 70 µm (coarse silt; Fig. 4.3k & l).

4.4.3 Sediment composition

The mean percentage abundance of sediment constituents at Middle Reef and Paluma Shoals were similar: coral (~32%) and mollusc fragments (25%) were the largest contributors to sediments; calcareous algae and alcyonian spicules contributed 7-10%, and foraminifera, echinoid spines, crustacean debris, annelids and *Halimeda* plates each contributed <5% to sediments (Fig. 4.4). The most common foraminifera observed within the sediments was *Amphistegina* (>50 % of the total foraminifera count). Other foraminiferans identified included *Marginopora, Calcarina* and *Quinqueloculina*. Differences in sediments collected from Middle Reef and Paluma Shoals include the abundance of non-carbonate material which was greater at Paluma Shoals (13%) than at Middle Reef (6%), and echinoid spine fragments (3%) which were only found at Middle Reef.

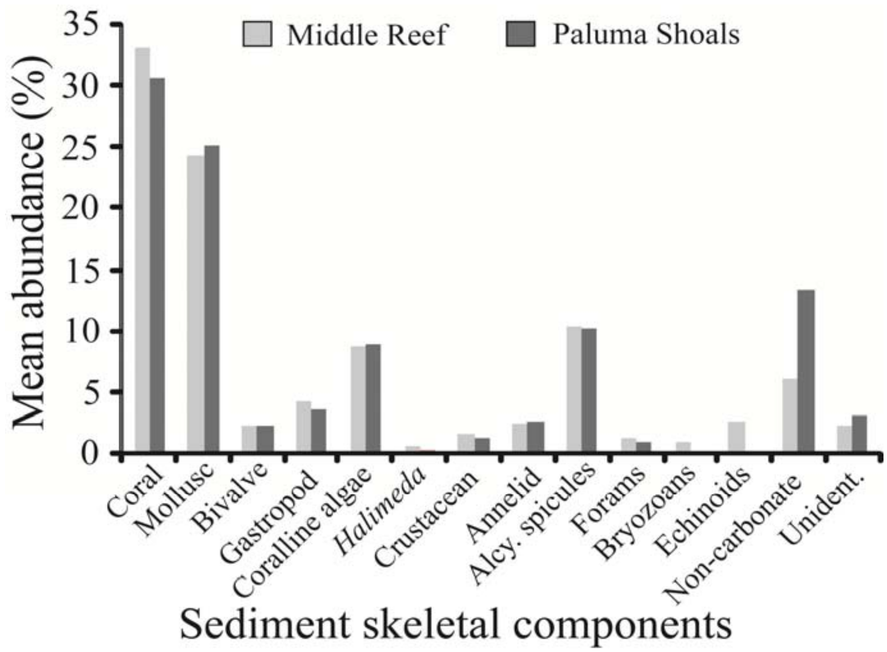

Figure 4.4: The mean percentage abundance of the thirteen sediment components at Middle Reef and Paluma Shoals.

Sediment constituents were classified into five size class fractions to determine if composition was correlated to particle size (Table 4.3). The mean percentage abundance of coral and mollusc fragments dominated the four largest size fractions (>33%; Fig. 4.5), but decreased with particle size at Middle Reef (r^2=0.729) and Paluma Shoals (r^2=0.365). The abundance of crustaceans also decreased with particle size at both reefs (r^2=0.965). *Halimeda* fragments were most abundant in the largest size fraction (<2%) whereas CCA, foraminifera, alcyonian spicules and echinoid spines were most abundant in the two smallest size fractions (<0.85 mm) and negatively correlated

Table 4.3. The sediment skeletal component correlations (R^2) with sediment particle size. Positive values indicate that as particle size increases, the skeletal components abundance also increases, and negative values indicate the reverse trend.

Sediment skeletal component	Middle Reef	Paluma Shoals
Coral	0.73	0.37
Mollusc	0.63	0.97
CCA	-0.30	-0.78
Crustaceans	0.95	0.98
Annelid	-0.06	0.11
Alcyonian spicules	-0.62	-0.64
Halimeda	0.10	-0.02
Foraminiferans	-0.81	-0.52
Echinoid spines	-0.80	N/A
Bryozoans	0.00	0.04
Non-carbonate material	0.10	0.09

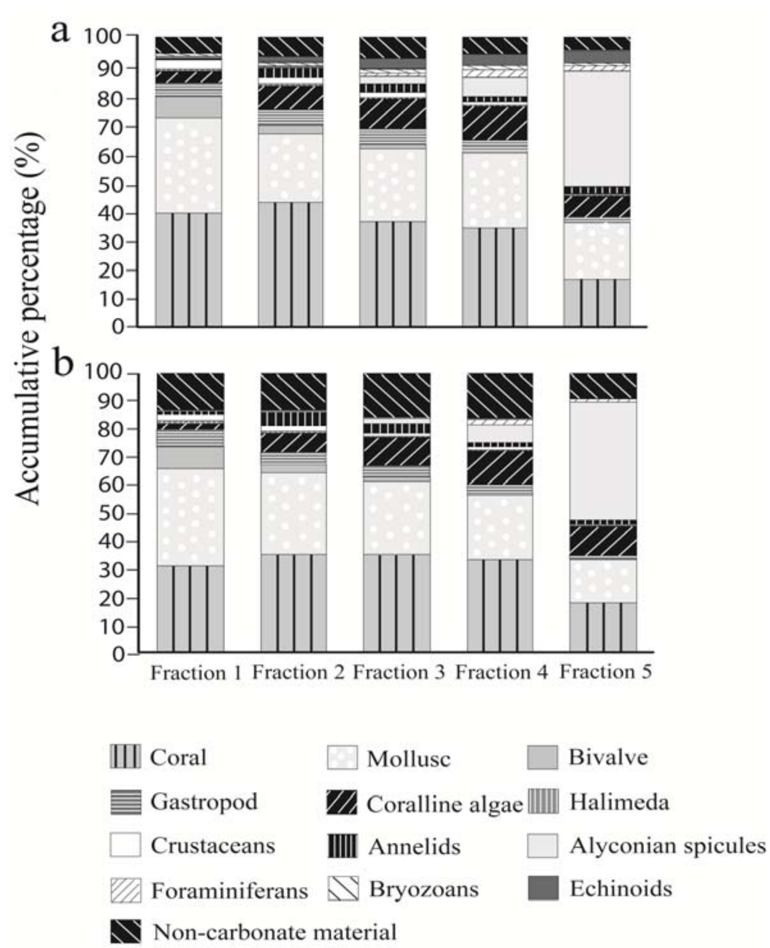

Figure 4.5: The abundance of skeletal components within each size fraction for (a) Middle Reef and (b) Paluma Shoals.

with particle size. The abundance of annelids and bryozoans were greatest in size fractions 2 (1.2 to 2 mm; Middle Reef = 3.3%; Paluma Shoals = 5%) and 3 (0.85 to 1.2 mm; Middle Reef = 1.2%; Paluma Shoals = 0.5%) respectively.

4.4.4 Sediment distribution

Spearman's rank correlation coefficient tests were conducted to determine if there was a significant increase or decrease in sediment textural characteristics (mean particle grain size, skewness and kurtosis, the percentage of gravel, sand and silt, carbonate content) and composition (sediment components) over the reef and with depth (Table 4.4).

Sediment textural characteristics

The mean particle size significantly decreased from the wave exposed eastern windward edge to the protected western basin at Middle Reef ($p=0.00$) and from the windward to leeward edge at Paluma Shoals ($p=0.03$). The mean particle size also significantly increased with depth at both reefs ($p<0.04$) due to a significant increase in the sediment sand content at deeper sites ($p<0.04$). At Middle Reef, the level of skewness and kurtosis significantly decreased westwards ($p=0.02$, $p=0.00$), and at Paluma Shoals the level of kurtosis ($p=0.06$) decreased from the windward to leeward edge.

Calcium carbonate content within the surficial sediments was highly variable at both reefs ranging from 7.8% to 89.7% at Middle Reef and 4.1% to 83.5% at Paluma Shoals. Calcium carbonate content significantly decreased westwards ($p=0.03$) at Middle Reef. In contrast, carbonate content at Paluma Shoals significantly increased westwards towards the leeward reef edge ($p=0.02$) on to the reef flat (depth $p=0.01$).

Table 4.4. Spearman's rank correlation coefficient tests for sediment textural characteristics and composition with location (north to south, east to west) and depth at Middle Reef and Paluma Shoals. Significant values are highlighted in bold.

Sediment Texture	North to south		East to west		Depth	
	Middle Reef	Paluma Shoals	Middle Reef	Paluma Shoals	Middle Reef	Paluma Shoals
Mean	0.47	**0.03**	**0.00**	0.27	**0.02**	**0.04**
Textural group	0.35	0.11	**0.00**	0.39	**0.02**	0.18
Skewness	0.33	0.29	**0.02**	0.38	0.25	0.14
Kurtosis	0.48	**0.06**	**0.00**	0.15	**0.01**	**0.02**
%age gravel	0.09	0.49	0.21	0.33	0.48	0.41
%age sand	0.40	**0.03**	**0.00**	0.29	**0.00**	**0.04**
%age silt	0.50	**0.03**	**0.00**	0.26	**0.00**	**0.02**
Carbonate content	0.11	**0.02**	**0.03**	**0.05**	0.32	**0.01**
Sediment skeletal component						
Coral	0.12	0.57	0.34	0.47	0.13	0.07
Unidentified mollusc fragments	**0.00**	0.12	0.17	0.41	0.25	0.35
Bivalves	0.26	**0.05**	0.24	**0.01**	0.47	**0.01**
Gastropods	0.07	0.432	0.39	0.14	0.48	0.10
Coralline algae	0.10	0.08	**0.02**	**0.00**	**0.04**	0.25
Crustacean	0.10	0.19	0.40	**0.02**	**0.02**	**0.02**
Annelid	0.19	0.07	0.27	**0.04**	0.13	**0.00**
Alcyonian spicules	**0.04**	**0.02**	0.09	**0.01**	0.39	**0.00**
Halimeda	0.31	0.48	**0.01**	**0.01**	0.50	0.25
Foraminiferans	0.16	**0.05**	**0.05**	**0.04**	**0.04**	**0.01**
Echinoid spines	0.06	N/A	0.34	N/A	0.39	N/A
Bryozoan	0.15	0.114	0.19	0.11	0.18	0.07
Non-carbonate material	0.07	0.12	0.26	**0.03**	**0.01**	0.06

Sediment constitutes

At Middle Reef, CCA sediments and crustacean fragments were significantly ($p<0.05$; Table 4.4) more abundant on the central windward reef flat and contrasted with foraminiferans which were more abundant in sediments collected from deeper sites along the leeward edge ($p<0.05$). Mollusc fragments and bivalves were also significantly abundant along the leeward edge ($p<0.05$) whereas alcyonian spicules were concentrated in sediments collected from the western windward reef edge

($p=0.04$). At Paluma Shoals the abundance of CCA, *Halimeda*, crustaceans, annelids and alcyonian spicules significantly increased from the eastern exposed windward reef edge onto the reef flat ($p<0.05$). CCA and *Halimeda* fragments were most abundant on the western windward edge and reef flat, annelids were more abundant on the central leeward reef edge and alcyonian spicules were most abundant on the central to western reef flat. In contrast, the abundance of foraminiferans increased with depth down the eastern windward reef slope ($p<0.04$). Bivalve fragments were also more abundant at deeper sites, but along the leeward reef edge ($p<0.05$).

Spearman's rank correlation coefficient tests were carried out to determine if sediment components were significantly correlated to benthic cover using benthic assemblage cluster groups. Five out of thirteen components (coral, CCA, crustaceans, foraminifera, non-carbonate material) were significantly related to benthic cover at Middle Reef ($p<0.05$; Table 4.5). Coral fragments were more abundant where coral cover was high (>50%), but CCA was more abundant where coral cover was low (<20%). Crustaceans were more abundant in reef habitats where macro-algal cover was high (>20%) and non-carbonate material was most abundant where sediment cover was high (>50%). At Paluma Shoals, only coral fragments were significantly correlated with benthic cover ($p=0.01$).

Table 4.5: Spearman's rank correlation tests to determine if sediment skeletal components are significantly correlated with benthic assemblages.

	Benthic assemblages	
Sediment components	**Middle Reef**	**Paluma Shoals**
Coral	**0.05**	**0.01**
Unidentified mollusc fragments	0.35	0.18
Bivalves	0.79	0.70
Gastropods	0.57	0.62
Coralline algae	**0.04**	0.38
Crustacean	**0.05**	0.40
Annelid	0.98	0.90
Alcyonian spinules	0.50	0.42
Halimeda	0.59	0.64
Foraminiferans	**0.05**	0.69
Echinoid spines	0.20	N/A
Bryozoans	0.50	0.18
Non-carbonate material	**0.02**	0.34

4.4.5 Sediment facies

Sediments were classified into sediment compositional groups using five factors extracted from a data matrix of thirteen sediment constituents. The five sediment factors explain 73% and 82% of the data variance at Middle Reef and Paluma Shoals respectively. Three out of five compositional groups were common to both reefs, and included a CCA, coral and non-carbonate group. The fourth compositional group was mixed, and the fifth compositional group was dominated by alcyonian spicules at Middle Reef and mollusc fragments at Paluma Shoals (Fig. 4.6). Sediment compositional and textural groups were combined to determine sediment facies (Table 4.6), and were overlaid on to the bathymetric image of the reefs together with benthic assemblage cluster groups (Fig. 4.7).

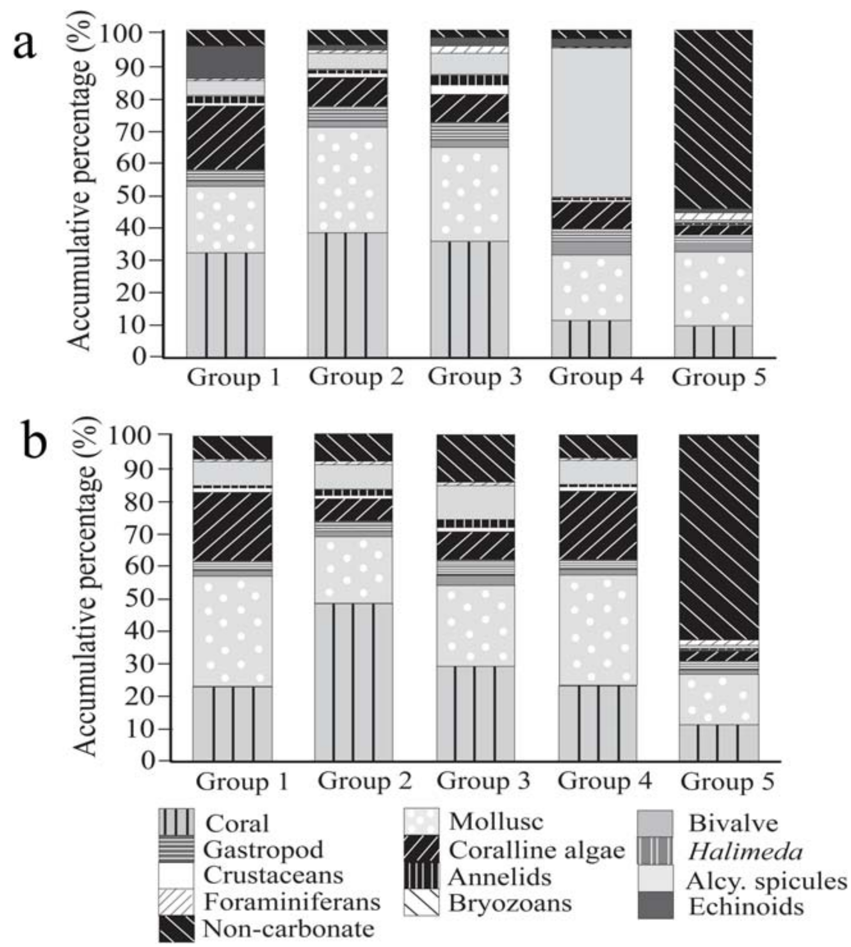

Figure 4.6: Sediment compositional groups for (a) Middle Reef and (b) Paluma Shoals. Group 1 is dominated by CCA, group 2 by coral fragments, group 3 is mixed, group 4 by alcyonian spicules at Middle Reef and mollusc fragments at Paluma Shoals, and group 5 by non-carbonate material.

Table 4.6: Sediment facies characteristics at Middle Reef and Paluma Shoals. The spatial distribution of sediment facies are described here and displayed on Figure 4.7 together with benthic community assemblage clusters.

Reef	Sediment facies group	Textural group	Dominant sediment component	Spatial distribution
Middle Reef	1	Slightly gravelly sand	Non-carbonate material	Base of the far eastern windward slope
	2	Slightly gravelly sand	Corals	Eastern reef slope to eastern leeward edge
	3	Slightly gravelly muddy sand	Mixed (Corals and molluscs)	Central section of eastern and western basin
	4	Muddy sand	Mixed (Corals and foraminiferans)	Central leeward edge
	5	Muddy sand	CCA and echinoids	Central windward reef edge and slope
	6	Slightly gravelly sandy mud	Corals	Far western end of the western basin and leeward edge
	7	Sandy mud	Alcyonian spicules	Far western windward reef edge and slope
Paluma Shoals	1	Slightly gravelly sand	Non-carbonate material	Base of the far eastern windward slope
	2	Slightly gravelly sand and sands	Mixed (Corals, molluscs, alcyonian spicules)	Central windward reef slope, and western reef flat
	3	Slightly gravelly muddy sand	Coral	Central windward reef edge towards the central reef flat
	4	Muddy sand	CCA	Western windward reef edge and slope
	5	Muddy sand	Coral	Central reef flat towards the leeward reef edge
	6	Sandy mud	Coral	Eastern leeward reef edge
	7	Sandy mud	Mollusc	Central leeward reef edge and slope

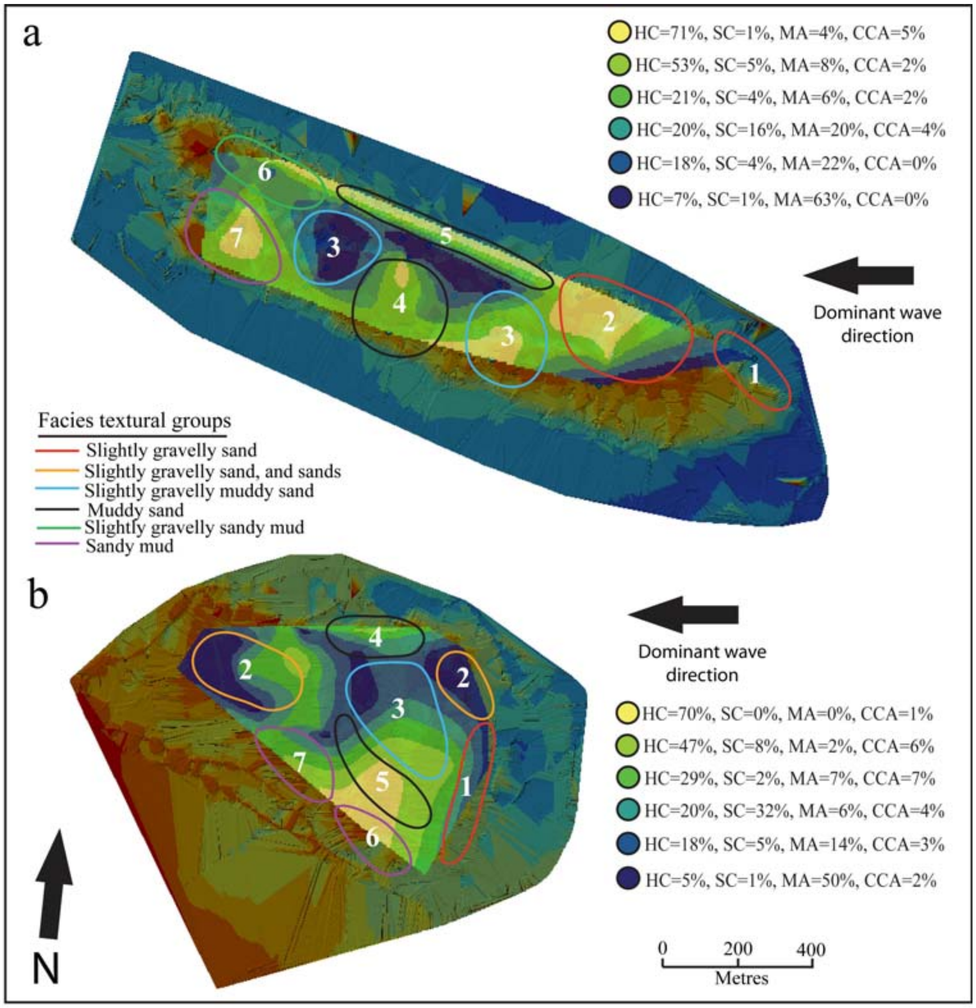

Figure 4.7: Benthic community assemblages and sediment facies distribution at (a) Middle Reef and (b) Paluma Shoals. Numbers 1 to 7 denote sediment facies which are described in detail in Table 4.6.

4.4.5.1 Middle Reef

The base of the far eastern windward reef slope had low coral cover (<10%) and was dominated by slightly gravelly sediments with a high non-carbonate component. Coral cover increased on to the eastern windward reef edge (71%) and coral dominated the slightly gravelly sands. The central areas of the eastern and western basin were composed of slightly gravelly muddy sands, dominated by coral fragments with a comparatively high proportion of mollusc fragments. Coral cover on the central windward and leeward reef edges ranged from 20 to 50%, macro-algal cover was low

(<10%) and sediments were largely composed of muddy sands. However, on the leeward edge, muddy sand were mixed with a higher abundance of foraminiferans, whereas on the windward edge CCA and echinoid fragments increased in abundance. The far western end of Middle Reef was composed of slightly gravelly sandy muds and sandy muds. Along the western windward reef edge these sediments had a high abundance of alcyonian spicules due to high soft coral cover (16%), and within the western central and leeward edge where coral cover was high (70%), sediments were characterised by coral fragments.

4.4.5.2 Paluma Shoals

At the base of the far eastern windward slope slightly gravelly sands were dominated by non-carbonate material. These reef habitats had low coral cover (<5%) and high sediment cover (>50%). Slightly gravelly sands also dominated the central windward reef slope and western reef flat, but sediments were mixed with a high abundance of coral fragments, molluscs, CCA and alcyonian spicules. The central windward reef edge and flat was composed of slightly gravelly muddy sands, and had a high abundance of coral fragments even though coral cover was low (<20%). The western windward reef edge had the highest CCA cover which was reflected in the high abundance of CCA in the muddy sands, whereas muddy sands collected from the central reef flat to the eastern leeward edge were dominated by coral fragments reflecting high coral cover (>70%). The finer sandy muds had collected along the leeward reef edge; towards the eastern end and were dominated by coral fragments and mollusc fragments towards the western end.

4.5 Discussion

4.5.1 Sediment texture

Sediments were polymodal and consisted of varying proportions of silt, sand and gravel, consistent with previous work on inshore sediments on the GBR (Larcombe *et al.*, 1995; Larcombe *et al.*, 2001). Six textural groups were identified at Middle Reef and Paluma

Shoals, of which four were common to both reefs. However, the mean particle size for each textural group was typically greater at Paluma Shoals due to higher wave energy and a winnowing of fine sediments. In contrast, Middle Reef is protected from strong winds and swell from the N by Magnetic Island, and wave energy is typically lower than at Paluma Shoals. Furthermore, Middle Reef has a complex reef morphology with protected inner reef habitats where fine sediments are deposited, whereas Paluma Shoals has an expansive reef flat subjected to high wave energy, particularly at low tide.

The distribution of sediments over Middle Reef and Paluma Shoals was influenced by spatial gradients in wave energy. Wave heights and energy were higher along the exposed windward reef edge and were lower on leeward edge due to reef morphological interactions with waves (Gourlay, 1994). Along the windward reef edges sediments had a larger mean particle size (slightly gravelly sands) and were well sorted. Particle size and the level of sorting significantly decreased on to the reef flats and towards the leeward reef edges where sediments were composed of poorly sorted sandy muds and slightly gravelly sandy muds. Fine sediments are transported across the reef to these protected reef habitats whereas the coarse sand and gravel component are mostly likely produced *in situ* but may also be transported here during high energy events. At Middle Reef, sandy muds were concentrated at the western end of the reef, from the windward to leeward edge, as opposed to along the leeward edge (as at Paluma Shoals) where fine sediments are typically found (Roy & Smith, 1971; Smithers, 1994), due to linear shape of the reef and the dominant E to SE wave direction.

4.5.2 Sediment composition

Similar carbonate sediment composition at Middle Reef and Paluma Shoals indicates that these sediments provide a sediment signature of coral reefs in terrigenous sedimentary settings subjected to wave-driven high turbidity events. Sediments were composed of on average 50-60% carbonate, which is higher than reported in sediments collected from the surrounding sea floor (<10%; Belperio, 1983) but consisted with previous sediment analysis by Larcombe and Costen (2001). Coral fragments were the dominant carbonate sediment component, and the percentage abundance of coral fragments was remarkably similar to the mean coral cover at both reefs suggesting that sediments reflect coral cover. Sediments were also composed of a high abundance of mollusc fragments (25%), which are known to be more abundant in reef habitats where muds are deposited (Masse *et al.*, 1989), and a lower abundance of CCA and alcyonian spicules (<10%) due to low CCA and soft coral cover (<5%). Carbonate sediments in terrigenous impacted reef environments, such as Middle Reef and Paluma Shoals, are often well preserved in the fossil record due to limited early digenetic dissolution of carbonate grains (Perry & Taylor, 2006). These results suggest that sediment composition on inshore turbid reefs reflect hard and soft coral cover, and CCA abundance, and may also provide a temporal record of benthic cover.

Sediments collected from Middle Reef were distinct from Paluma Shoals in the relative abundance of the non-carbonate material (Middle Reef=6%, Paluma Shoals=13%), and also the presence of echinoids spine fragments (Middle Reef = 3%, Paluma Shoals = 0%). Non-carbonate material was more abundant at Paluma Shoals because it was situated close to shore, whereas sediments at Middle Reef contained echinoid spines due to the presence of *Diadema*. *Diadema* have been observed in low numbers (<1 per transect) within the western central basin and along the central windward reef slope, whereas no *Diadema* have been observed at Paluma Shoals (unpublished data). A high abundance of echinoids on reefs is often associated with high fishing pressure (Silva & McClanahan, 2001) and/or high algal cover, indicative of a coral-algal phase shift and deteriorating reef stability. Mean macro-algal cover was marginally higher at Middle Reef (14%) than at Paluma Shoals (10%), which could be related to elevated nutrient (nitrates, phosphates) concentrations in Cleveland Bay (Scheltinga & Heydon, 2005), and was particularly high (30-60%) along the windward reef edge where echinoid spines were most abundant. However, macro-algal cover is still comparatively low at both reefs, despite elevated nutrients recorded in waters near Middle Reef, which may in part be due to the synergistic effects of high turbidity and sedimentation.

4.5.3 Sediment distribution

The distribution of CCA, foraminiferans and mollusc fragments were significantly correlated to wave exposure and depth at Middle Reef and Paluma Shoals reflecting preferences for either high or low energy environments. CCA are typically more common in sediments in high energy environments (Hewins & Perry, 2006), and were most abundant in sediments on exposed sections of the reef flat, but found in low abundance within sediments in low energy, low light environments (Masse *et al.*, 1989) such as the base of the reef slopes. Foraminiferans are also influenced by wave energy (Renema, 2006) and were found to be most abundant in gravelly muddy sands collected at depth (>-2 m) from exposed reef edges, and least abundant within sandy muds concentrated within sheltered reef environments. Sandy muds have a lower critical shear stress and are more easily resuspended resulting in large and rapid fluctuations in turbidity (Larcombe *et al.*, 1995). Light availability is considered to be an important factor influencing foraminifera abundance and distribution (Uthicke & Nobes, 2008), and may explain their low abundance on these turbid reefs, and in reef habitats subjected to large fluctuations in turbidity. In contrast, mollusc fragments were found in greater abundance within the sheltered reef habitats where muddy sands to sandy muds were deposited. These spatial variations suggest that these calcifying organisms, although in low abundance in sediments, can provide information on the hydrodynamic and sedimentary setting on inshore turbid reefs.

4.5.4 Sediment and benthic interactions

Spatial variations in sediment composition were related to benthic cover at Middle Reef but not at Paluma Shoals due to higher wave resuspension and redistribution of sediments. At Middle Reef, coral, CCA fragments, crustaceans, foraminiferans and non-carbonate material were significantly correlated with benthic cover indicating a degree of biological control on both sediment composition and distribution. In contrast, only coral fragments were significantly correlated to benthic cover at Paluma Shoals, which suggests that although, composition is related to benthic cover, sediment distribution is largely controlled by the hydrodynamic regime. Nevertheless, there were a number of similarities in the distribution of sediments facies over Middle Reef and

Paluma Shoals due to comparable wave directions which influenced textural distribution, and benthic cover which influenced sediment composition.

4.6 Conclusions

The study of grain size, texture and composition of sediments collected from the reef surface at Paluma Shoals and Middle Reef has led to the following conclusions:

- Sediments were polymodal, composed of approximately 50% carbonate and included coarse (slightly gravelly sands) to fine (sandy muds) sediments.
- Six textural groups were identified, four of which were common to both reefs. The mean particle size for textural groups was typically greater at Paluma Shoals due to greater sediment resuspension and winnowing of fine sediments.
- Differences in grain size characteristics reflect hydrodynamic differences between reef sites and over reefs.
- Reef morphology has a significant influence on the distribution of sediments. The mean grain size and kurtosis decreased from the base of the windward slope onto the reef flat in the direction of the dominant wind and waves.
- Coral and mollusc fragments dominate the sediments. Minor components found at both reefs include CCA, *Halimeda* fragments, annelids and worm casings, crustacean debris, alcyonian spicules, foraminifera and non-carbonate material.
- The mean sediment composition at both reefs reflected mean benthic cover, indicating that carbonate sediments reflect reef carbonate productivity despite high terrigenous sediment loads. Consequently, well preserved carbonate sediments in the fossil record could provide a temporal assessment of benthic productivity.
- At Middle Reef, five skeletal components (coral, CCA, foraminiferans, crustaceans, non-carbonate material) were significantly correlated to benthic cover. This indicates a degree of biological control on sediment composition and distribution, and limited redistribution of sediments.
- At Paluma Shoals, only coral fragments were significantly correlated to benthic cover suggesting that on reefs subjected to higher wave energy and sediment redistribution, hydrodynamics are the primary control on sediment distribution.

- In summary, similar sediment facies composition (and distribution) suggests that these sediments provide a reef signature for inshore turbid reefs.

5. SPATIAL AND TEMPORAL VARIATIONS IN TURBIDITY ON TWO INSHORE TURBID ZONE REEFS ON THE GREAT BARRIER REEF, AUSTRALIA

To be submitted to Journal of Marine and Freshwater Research (September 2011)

5.1 Abstract

This study describes the natural turbidity regime at two inshore turbid reefs on the Great Barrier Reef (GBR) where wind-driven waves are the main agent of resuspension and can produce large fluctuations in turbidity. Many corals on inshore turbid reefs have adapted to high and fluctuating turbidity regimes, however, anthropogenic activities such as dredging and coastal development are speculated to produce larger and more prolonged turbidity events that may exceed the adaptive capacity of corals on these reefs. A good understanding of the natural turbidity regime is required to determine if and when coral communities on inshore turbid reefs are at risk from increased sediment delivery and high turbidity events. Two reefs were examined in this study: 1) Middle Reef, a semi-protected reef located between Magnetic Island and Townsville; and 2) Paluma Shoals, located in Halifax Bay where it is exposed to higher energy wind and waves. Instruments were deployed at exposed and sheltered locations on each reef for 14 days in 2009 to measure spatial and temporal variations in turbidity and its driving forces (waves, currents, tides). Locally driven wind-waves were the key driver of turbidity, but the strength of the relationship was also dependent on wave exposure. As such, turbidity varied over the reef and was reflected in the community assemblage distribution with a high abundance of heterotrophic corals (e.g. *Goniopora*) in reef habitats subjected to large fluctuations in turbidity (>100 NTU). A turbidity model was developed using local wind speed data which explained <77% and <56% of the variance in turbidity at Paluma Shoals and Middle Reef, respectively. The model was able to predict naturally high turbidity events and can, therefore, be used by future researchers to determine if the frequency and severity of turbidity events is rising due to increased sediment delivery to inshore regions of the GBR.

5.2 Introduction

Corals living in clear-water environments depend on the photosynthetic properties of zooxanthellae algae within the coral to convert light to energy for metabolic functions including growth, reproduction and immunity (Rinkevich, 1989; Al-Horani *et al.*, 2003). If light levels are reduced, energy production is impaired and coral survival maybe compromised. There are four main determinants that influence light availability in water (Anthony & Connolly, 2004): seasonal pattern of daily surface irradiance (Kirk, 1994), variations in cloud cover (Mumby *et al.*, 2001), tidal movements (Kleypas, 1996) and turbidity which reduces light transmittance through the water column (Van Duin *et al.*, 2001). Corals on inshore turbid reefs on the central Great Barrier Reef (GBR) are subjected to large fluctuations (>50 NTU) in turbidity due to wind-driven resuspension (Lou & Ridd, 1996; Larcombe *et al.*, 2001; Orpin *et al.*, 2004), which accounts for >70% of the annual variation in light irradiance at only 1.5 m below the sea surface (Anthony *et al.*, 2004). Consequently, the most successful corals in inshore turbid waters have adapted to become at least partly heterotrophic, feeding on a range of food types including plankton (Sebens *et al.*, 1996), bacteria (Bak *et al.*, 1988) and suspended particulate matter (Anthony & Fabricius, 2000). Inshore turbid reefs represent approximately one third of reefs on the GBR and are within 20 km of the mainland coast, often within close proximity to heavily modified urban and agricultural catchments. Sediments are delivered to inshore regions through land and river runoff which has reportedly increased by five to ten-fold since European settlement (McCulloch *et al.*, 2003), raising concerns regarding the upper turbidity threshold that corals can survive.

To determine if sediment delivery and turbidity have increased, and whether any increase threatens inshore turbid reefs, the natural turbidity regime must be described. Wind-driven waves are the dominant control on sediment resuspension and turbidity on the GBR inner-shelf (Wright, 1995; Lou & Ridd, 1996; Orpin *et al.*, 2004), and, thus, models have been developed that predict turbidity using wind data alone (Lou & Ridd, 1997; Whinney, 2007). These models are based on the theory that the shear bed stress is a function of the square of the bottom wave orbital velocity (Lou & Ridd, 1996), which is linearly related to the wave height, and is approximately proportional to the square of the wind speed (WMO 1998). However, these models predict regional scale

(>10 km's) changes in turbidity and, therefore, do not recognise intra-reef (<1 km) variations that are particularly pronounced on inshore turbid reefs. It is important to consider these small scale variations as they influence benthic cover, coral composition and distribution, and ultimately reef growth. For inshore reefs situated close to anthropogenic developments, knowledge on sediment delivery and distribution over the reef will be critical for assessing if sediment loads and turbidity are increasing, and for documenting the probable influence on reef communities.

This study investigates spatial and temporal variations in turbidity on Middle Reef and Paluma Shoals, two inshore turbid reefs on the central GBR, and discusses the implications of turbidity gradients on coral communities on each reef. Middle Reef is situated in a semi-enclosed bay, within close proximity of a large expanding city (Townsville) and busy international port. Paluma Shoals is situated in an exposed position in a large open bay where there has been limited coastal development. Specifically, I: (1) examine spatial and temporal variations in turbidity and its driving forces (waves, currents, tides); (2) identify quantitative relationships between driving forces and turbidity levels; (3) assess the influence of spatial variations in turbidity on coral community composition; and (4) devise a model to predict site-specific temporal variations in turbidity. The site-specific model will enable future researchers to direct real-time management for turbidity risk assessment, identify increases in turbidity levels above the natural turbidity regime, and assess the implications for coral communities and reef health.

5.3 Materials and Methods

5.3.1 Study sites

The hydrodynamic and turbidity regime were measured at an exposed and sheltered location on Middle Reef and Paluma Shoals (Fig. 4.1; refer to section 4.3 for detailed description of study area and sites). At Middle Reef, the semi-exposed location was on the eastern windward edge where coral cover was high (54%) and sediments consisted of slightly gravelly sands, and the sheltered location was in the western basin where coral cover was low (20%) and the sediments were muddy sands (Table 5.1). At Paluma Shoals, the exposed location was on the northern windward edge where coral cover (50%) was dominated by large strands of *Goniopora* and sediments were muddy sands, and the sheltered location was along the southern leeward reef edge where coral cover (39%) was dominated by large *Galaxea* colonies interspersed with pools lined with sandy muds.

Table 5.1: Site locations at Middle Reef and Paluma Shoals including information on sedimentary characteristics and benthic cover.

Reef	Site	Depth (m) at LAT	Sediment	Hard coral cover (%)	Diversity (H')	Dominant corals	Macro -algal cover (%)	Sand/silt cover (%)
Middle Reef	Semi-exposed site at the eastern end of Middle Reef	-1	Slightly gravelly sand Mean=365µm Polymodal Moderately sorted $CaCo_3$ = 83%	54	1.13	*Acropora* and plate *Montipora*	8	25
	Sheltered site within the western basin	-1.5	Muddy sand Mean=250 µm Polymodal Very poorly sorted $CaCo_3$ = 77%	20	1.27	Plate *Montipora*, *Porites* bombies, *Turbinaria* and *Acropora*	25	25
Paluma Shoals	Exposed site at the base of the northern windward reef slope	-2	Muddy sand Mean=170 µm Polymodal Poorly sorted $CaCo_3$=21%	50	0.9	Large stands of *Goniopora*	<5	50
	Sheltered site at the southern leeward reef edge	-2	Sandy mud Mean=30 µm Polymodal Poorly sorted $CaCo_3$= 25%	39	1.2	Large stands of *Galaxea* and *Goniopora*	<10	25

5.3.2 Sensor deployment

Field measurements were taken at the start of the dry season during the months of April-May 2009 for approximately two weeks. Wave, current and tide measurements were collected using a Nortek 2 MHz Acoustic Doppler Current Profiler (ADCP), and turbidity was measured using an optical backscatter device, commonly called a nephelometer (Ridd & Larcombe, 1994).

Wave measurements were taken every 20 minutes during the survey period. Measurements included the significant wave height (H_{sig}), the mean (T_{m02}) and peak wave period (T_{peak}), and the mean wave direction. The sampling frequency was 2 Hz and the burst length was 512 seconds. The mean current strength and direction for 20 cm depth bins vertically above the data logger were recorded every 10 min for up to 4 m into the water column to provide a current profile with depth. ADCPs were mounted on a square aluminium frame approximately 30 cm off the sea floor weighted down with a 20 kg weight to ensure instrument stability throughout deployment. Wave and current data were analysed using STORM, a data management, processing and viewing tool for Nortek instruments.

Turbidity measurements were recorded every 10 minutes, and represented the average of 1000 readings taken over a 1 minute sampling period. Sensors were equipped with an anti-fouling wiper which was activated every 2 hours. The nephelometer was calibrated before deployment to the standard 200 NTU. In this chapter, turbidity readings are given in NTUs, but can be converted to a suspended sediment concentration (mg/L), given that at Middle Reef and Paluma Shoals 1 NTU equals 2.2 mg/L (P. Ridd, pers. comms.). Nephelometers were mounted on a heavy steel frame that raised the instrument ~10 cm off the sea floor.

5.3.3 Meteorological data

Half-hourly wind data were obtained from an Australian Institute of Marine Science (AIMS) weather station, located on the S5 shipping Platypus channel marker in Cleveland Bay (Fig. 1.1). The weather station is approximately 7 km NE of Middle Reef and 30 km SSE of Paluma Shoals. Local wind data ($km.hr^{-1}$) was categorised with sea states as defined by the Australian Bureau of Meteorology (still <10, calm 10<20, slight 20<30, moderate 30<35, rough 35<45, very rough >45 $km.hr^{-1}$). Rainfall in Townsville during the sampling period was negligible with only a few light showers in early May (<3.4 mm).

5.3.4 Model development

Correlation and regression analysis was performed in SPSS 17 to determine if local wind speed data could be used to predict turbidity at Middle Reef and Paluma Shoals, and therefore develop a turbidity model. Spearman's rank tests established if wind strength was correlated to wave height, wave period, current speeds and turbidity, and regression analysis was performed on the square of the average wind strength data for 1, 3, 6, 12, 24 and 72 hrs to determine how much variance in turbidity was accounted for by wind speed data alone. The square of the wind speed was used to provide a more accurate representation of wind energy available to generate to wind-driven waves (Orpin *et al*., 2004).

Linear regression analysis produced a model for predicting half hourly turbidity responses to wind speeds (Eq. 1).

$$\text{Turbidity} = [\text{Antilog}\ (b0 + (b1 \times \text{wind speed}^{c}))]^{2} \qquad \textit{Equation 1}$$

where c is the power to which the wind speed is weighted and b (0,1) are constant values specific to each site generated following regression analysis. The model was tested using turbidity data collected in June/July 2010 at the same reef locations. Wind direction during the model development phase (April-May 2009) was predominately from the E to SE and winds during the test survey conditions were predominately from the SE to S.

5.4 Results

5.4.1 Spatial variations in waves, currents and turbidity

5.4.1.1 Middle Reef

Wave heights were higher at the exposed eastern windward reef edge at Middle Reef (H_{sig}=0.21) and decreased westwards (H_{sig}=0.17; Table 5.2, Fig. 5.1). Wave heights >0.15 m approached from the east (E) to south-east (SE) at both instrument locations (Fig. 5.2) and the typical mean wave period was 2-3 s, with longer wave periods (> 4 s) more frequent (15.8%) at the exposed eastern location (Table 5.2). At the western basin, wave periods oscillated with the tides; at low tide wave periods were typically

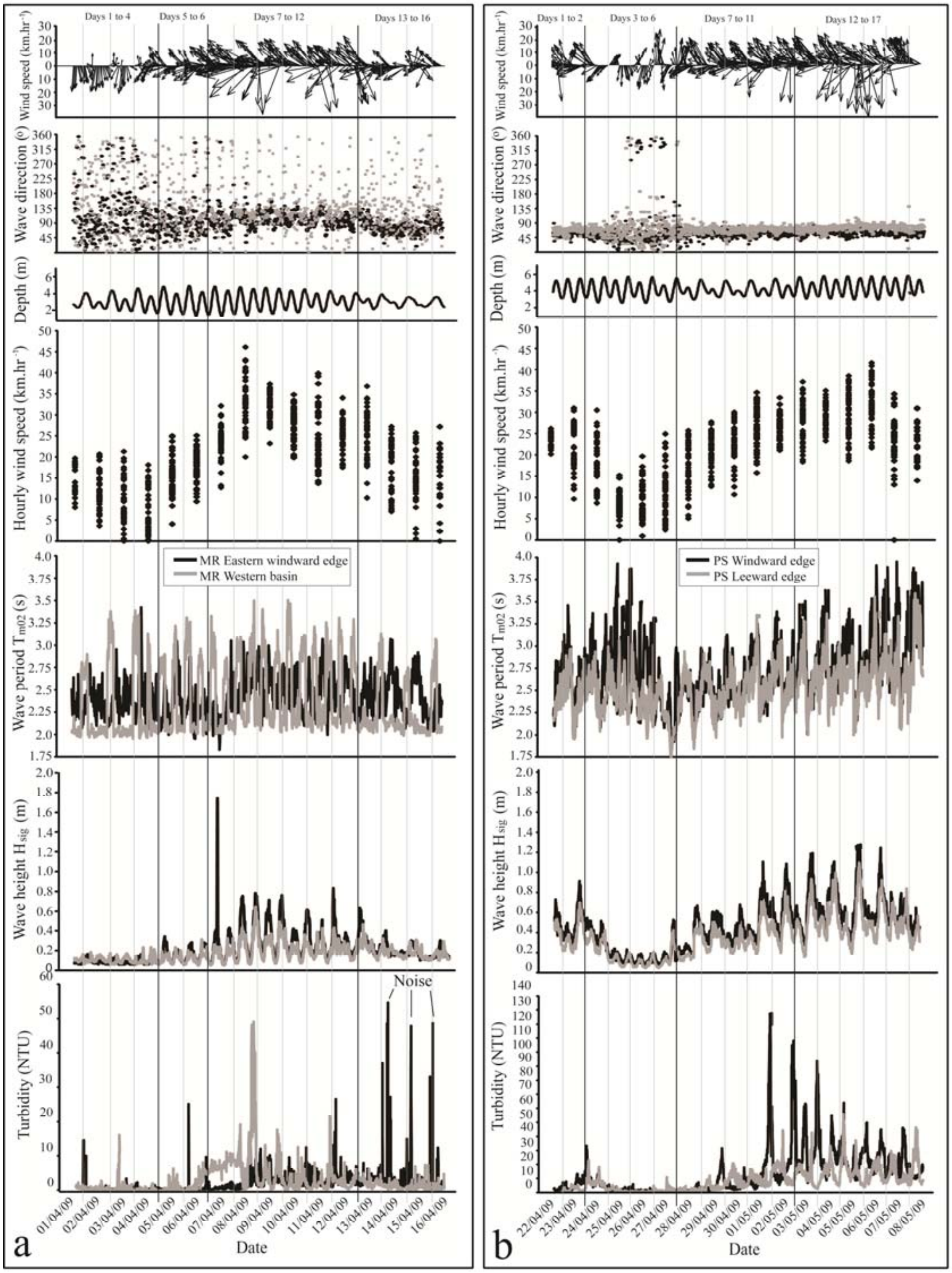

Figure 5.1: Wind, wave and turbidity data for (a) Middle Reef (MR) and (b) Paluma Shoals (PS). At the eastern site at Middle Reef, low turbidity during days 14-16 were punctuated with large fluctuations in turbidity (>50 NTU). These increases are isolated readings which did not coincide with wind and wave conditions indicating that these measurements were noise. Note the different scales in turbidity for Middle Reef and Paluma Shoals.

Table 5.2: Summary of wave dynamics and turbidity responses at Middle Reef and Paluma Shoals.

Reef	Site	Wave periods					Significant wave height (m)			Frequency (%) of Turbidity (NTU)					
		<3 s	<4 s	<5 s	<6 s	<7 s	Mean	Min	Max	<5	5 to 10	10 to 15	15 to 20	20 to 50	>50
Middle Reef	**Eastern**	71. 9	84.2	87.7	93.9	95.8	0.21	0.06	1.74	92.4	5.9	1.0	0.1	0.5	0.0
	Western	67.8	97.9	99.7	99.7	100	0.17	0.05	0.64	82.8	13.4	1.9	0.7	1.2	0.0
Paluma Shoals	**Windward**	37.2	59.6	89	100		0.48	0.09	1.27	40.0	13.7	14.1	9.3	19.8	3.1
	Leeward	50.8	77.6	92.3	99.7	100	0.38	0.06	1.09	41.1	28.2	13.6	9.5	7.4	0.2

Table 5.3: Results from Spearman's rank correlation and linear regression analysis at Middle Reef and Paluma Shoals. Correlations are at the 0.05 significance level except for numbers in italics which are at the 0.1 significance level.

Spearman's rank correlation coefficient		Wind strength versus wave height	Wind strength versus wave period	Wind strength versus wave direction	Wave height versus top current speeds	NTU versus wave height	NTU versus wave period	NTU versus top current speeds	NTU versus wind strength
Middle Reef	**Eastern**	0.528	*0.087*	0.239	-0.355	0.508	0.238	-0.415	0.549
	Western	0.473	0.269	*NS*	*-0.103*	0.487	0.239	*NS*	0.57
Paluma Shoals	**Windward**	0.75	*0.088*	*0.17*	0.587	0.752	0.245	0.418	0.394
	Leeward	0.733	0.228	0.237	0.232	0.473	0.394	*NS*	0.599
Linear regression analysis		**Hourly wind**	**3hr wind average**	**6hr wind average**	**12hr wind average**	**24hr wind average**	**72hr wind average**		
Middle Reef	**Eastern**	0.25	0.27	0.30	0.38	0.48	0.53		
	Western	0.24	0.30	0.27	0.23	0.17	0.02		
Paluma Shoals	**Windward**	0.40	0.43	0.48	0.60	0.63	0.56		
	Leeward	0.48	0.58	0.65	0.71	0.73	0.70		

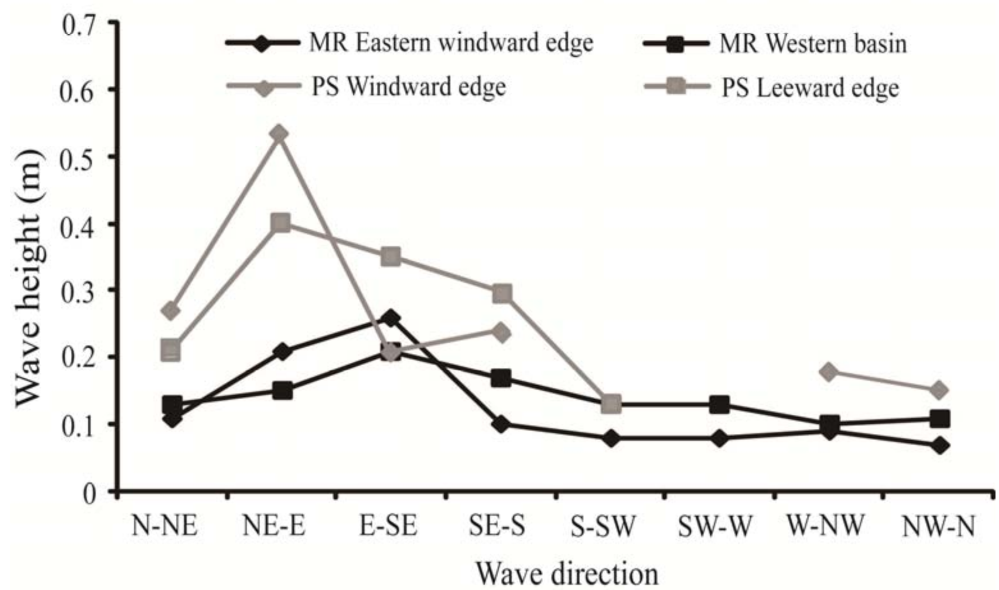

Figure 5.2: The mean significant wave height with wave direction at an exposed and sheltered location on Middle Reef (MR) and Paluma Shoals (PS).

2 s but increased to >3 s at high tide (Fig 5.1a).

At the sea bed current speeds were typically around 4 $cm.s^{-1}$, increasing to 6 $cm.s^{-1}$ at mid water depth (1-2 m), and 8 $cm.s^{-1}$ below the sea surface, with ebb tide currents stronger than flood tide currents (Fig. 5.3). During neap tides, currents flowed to the NW at <5 $cm.s^{-1}$ (13-16/04/09; Fig. 5.4a & b) whereas during spring tides, currents flowed to the NW-W on the rising tide and to the SE during on the falling tide, with currents >15 $cm.s^{-1}$ from the mid water depth to the sea surface (04-08/04/09; Fig. 5.4c & d). However, when N winds >25 $km.hr^{-1}$ blew, NW-N currents occurred during both the flood and ebb tides.

Turbidity levels were <5 NTU for more than 80% of the time at Middle Reef, increasing to >10 NTU in response to rising wind speeds and elevated wave activity (Table 5.2). Turbidity events >10 NTU occurred during days 7 to 12 when strong SE winds blew (>20 $km.hr^{-1}$), and the maximum significant wave height increased from <0.4 m to >0.8 m on the exposed windward edge and to >0.6 m in the sheltered western basin. Each >10 NTU event lasted for approximately 6 hrs, but the lag time in turbidity responses

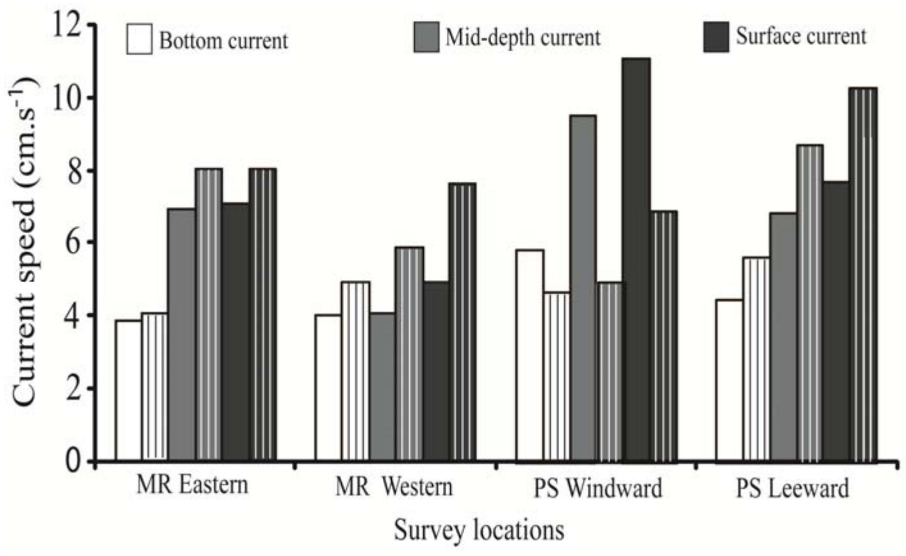

Figure 5.3: The mean current speed along the sea bed, mid way through the water column and at the sea surface during the flood (full bars) and ebb tide (striped bars).

and turbidity peaks varied over the reef. In the western basin turbidity levels increased on day 5 when wind speeds increased >15 km.hr^{-1}, and fluctuated between 0 to 10 NTU with large increases to >40 NTU following strong winds from the N. However, at the eastern end of the reef turbidity levels increased on day 9 and rarely exceeded 10 NTU even when strong winds (>30 km.hr^{-1}) blew. A weak tidal signature in turbidity levels was observed during the spring tides, with elevated turbidity readings occurring after the high tide.

5.4.1.2 Paluma Shoals

Wave heights were larger on the windward edge (H_{sig}=0.48 m) with larger waves (>0.3 m) typically approaching from the NE-E, whereas on the leeward edge the mean wave height was 20% lower (H_{sig}=0.38 m) with waves >0.3 m approaching from the NE-SE (Fig. 3). Wave periods > 4 s were more frequently observed on the windward edge (40.4%; Table 2), although no waves with periods >7 s were observed at both locations.

Currents were typically <8 cm.s^{-1}, with stronger currents (<12 cm.s^{-1}) at the sea surface (Fig. 5.3). However, stronger currents occurred during the flood tide at the windward edge, and during the ebb tide at the leeward reef edge. During neap tides current flow

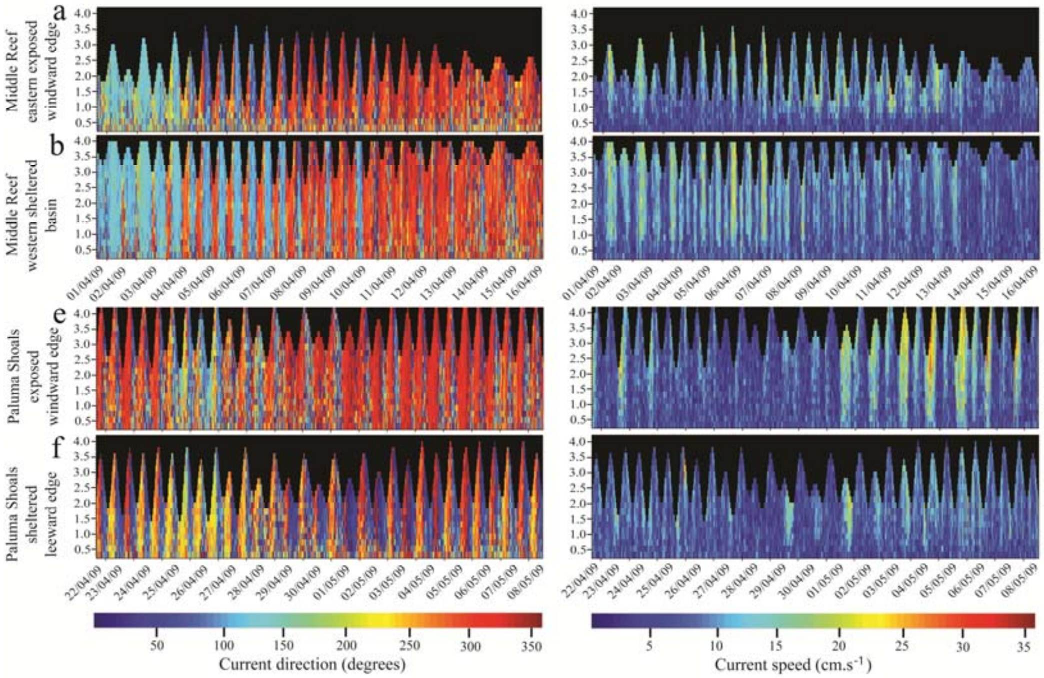

Figure 5.4: Current speed and direction throughout the water column at the eastern site (a,c) and the western basin at Middle Reef (b,d), and the windward edge (e,g) and leeward edge at Paluma Shoals (f,g).

oscillated, with NW-W currents moving across the windward and leeward reef edge during the rising tide, and to the SE-E during the falling tide (Fig. 5.4e & f). Current speeds were low (<10 $cm.s^{-1}$) throughout the water column at both locations until strong SE winds (>30 $km.hr^{-1}$) blew during spring tides (03-05/05/09; Fig. 5g & h). During these strong winds, currents flowed to the NW and increased to >15 $cm.s^{-1}$ on the leeward reef edge and >30 $cm.s^{-1}$ on the windward reef edge.

Turbidity levels were greater at Paluma Shoals than at Middle Reef despite comparable wind conditions. Turbidity levels <5 NTU occurred at Paluma Shoals for approximately 40% of the survey period, increasing to >10 NTU for 31% of the time on the leeward edge and 46% of the time on the windward edge (Table 5.2). Large responses in turbidity (>20 NTU) occurred on days 11 to 17 when moderate SE winds (<20 $km.hr^{-1}$) were punctuated with strong winds from the N (>30 $km.hr^{-1}$), and the maximum significant wave height increased from <0.6 m to >1.2 m on the windward edge, and to >1.0 m on the leeward edge (Fig. 5.1b). The response in turbidity varied, with turbidity increasing to >80 NTU on the windward edge during the flood tide, and

>50 NTU on the leeward edge at high tide, with each turbidity peak lasting approximately 3-4 hours.

5.4.2 Controls on turbidity

Turbidity levels increased rapidly following 12 to 24 hours of strong winds and elevated wave activity, although more rapid responses in turbidity were also observed following just three hours of elevated wave activity (e.g. >100 NTU was observed on the windward edge at Paluma on the afternoon of 01/05/09; Fig. 5.1b). To determine the strength and significance of these correlations, Spearman's rank correlation tests were performed between wind speed data, wave data, current speeds and turbidity data (Table 5.3). Wind strength was strongly positively correlated to wave height at both reefs (rho>0.47), but not to wave period or wave direction (rho<0.27). Correlations between wind and waves were strongest at Paluma Shoals, the more exposed reef, but were also stronger at the more exposed locations at each reef (rho>0.5). Correlations between waves and current speeds were variable: at Middle Reef correlations were negative and weak (rho<-0.35), whereas at Paluma Shoals, correlations were positive (rho>0.23). Current speeds were not significantly correlated with turbidity at reef locations, however, turbidity was positively correlated with wave height (rho>0.47), wave period (rho>0.23), and wind strength (rho>0.39).

5.4.3 Modelling turbidity

Regression analysis was conducted between wind strength and turbidity data to determine how much of the variance in turbidity was attributed to the wind strength. Turbidity data revealed a time lag between rising wind speeds and increases in turbidity. As such regression analysis was conducted using 1, 3, 6, 12, 24 and 72 hr averaged wind speeds. At Paluma Shoals, 24 hr averaged wind speeds accounted for the largest variation in turbidity; 63% and 73% on the leeward and windward edge respectively (Table 5.3). At the windward reef edge at Middle Reef, 24 hr averaged wind speeds accounted for 48% of the variance in turbidity, and 72 hr averaged wind speeds accounted for 53% of the variance. However, at the sheltered western basin it was the 3

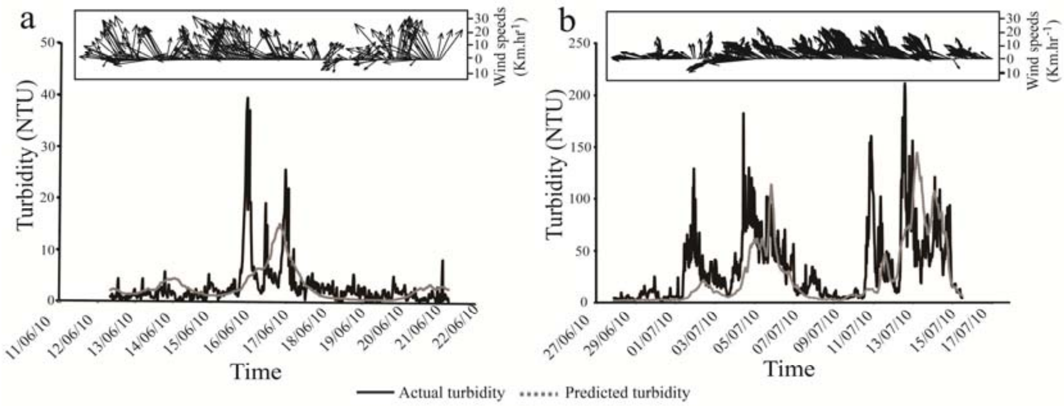

Figure 5.5: Actual and predicted turbidity based on the model developed using 2009 turbidity data. (a) The western basin at Middle Reef where the model explains 17% of the variance in turbidity. (b) The windward site at Paluma Shoals where the model explains 73% of the variance in turbidity. Note the different turbidity scales.

hr averaged wind speeds that accounted for the largest amount of variance in turbidity (30%).

Regression analysis of turbidity data from each instrument location provided the constant values (b0, b1) for Equation 1, which were then used to model turbidity using wind speed data. The model was tested using wind data collected in 2010, and predicted turbidity data was compared to actual turbidity collected during the same time period. The model which explained the most variance (73%) in turbidity was used to predict turbidity levels on the windward edge at Paluma Shoals in July 2010, and the model which explained the least variance (17%) using 24 hour average wind speeds was used to predict variance in turbidity in the western basin at Middle Reef in June 2010 (Fig. 5.5). The turbidity model for Paluma Shoals closely tracks real turbidity although the model predictions were consistently lower (by approximately 25%) and peaks occurred approximately 3 hours following the actual event. The model for the western site at Middle Reef also predicted large turbidity events observed in the field despite the model only accounting for 17% of the variance in turbidity, but again the predicted peak values were approximately 25% lower than in the field. Both models failed to predict one high but short-lived turbidity event; at Paluma Shoals this occurred on the 11/07/10 and on the 16/06/10 at Middle Reef.

5.5 Discussion

5.5.1 Spatial and temporal variations in turbidity

Data collected from Middle Reef and Paluma Shoals provide further evidence that corals on turbid reefs can survive rapid increases in turbidity to levels >20 NTU following wind-driven resuspension events, however, these events are short-lived, with peak turbidity lasting 3-4 hrs and returning to <5 NTU within 12 hrs. The response in turbidity varied between reef sites with larger fluctuations in turbidity occurring at Paluma Shoals than at Middle Reef. Paluma Shoals is exposed to higher waves than at Middle Reef due to the larger fetch which results in a higher sediment resuspension and larger fluctuations in turbidity. In contrast, Middle Reef is protected by Magnetic Island within a semi-enclosed bay where fetch is restricted, limiting wave heights and sediment resuspension rates.

Spatial variations in turbidity were also evident between the two instrument locations at Paluma Shoals and Middle Reef. Previous assessments have reported spatial variations at the scale of >10 km's (Larcombe *et al*., 1995; Larcombe *et al*., 2001), but studies at the intra-reefal scale (< 1 km) are rare. Turbidity levels at Paluma Shoals were <10 NTU across the reef during calm to moderate seas, but during rough seas, turbidity was in the order of 2 to 3 times greater on the windward edge where wave energy was high, than on the leeward reef edge. Furthermore, field observations at low tide show that wave resuspended sediments on the windward edge were trapped in front of the reef on the rising tide resulting in turbidities >100 NTU. In contrast, turbidity was greater at the sheltered western basin at Middle Reef (17% at >5 NTU) where wave energy was lower than at the exposed eastern windward edge during rough seas (9% at >5 NTU). These spatial differences in turbidity responses resulted from differences in sediment composition as evidenced from the lag times in turbidity responses. Muddy sands (<200 µm) in the western basin are more easily resuspended resulting in rapid and large fluctuations in turbidity. Furthermore, large turbidity peaks were prolonged (>6 hrs) as limited wave activity within the confines of the western basin effectively 'trapped' suspended sediments. In contrast, muddy sands are winnowed away from the windward edge and coarse sands (<500 µm) are deposited. These spatial variations in sediment composition are due to decreasing energy as waves travel over reefs (Roberts &

Murray, 1983; Gourlay, 1994; Hoitink, 2004), and acts to further reinforce spatial variations in turbidity responses.

5.5.2 Controls on turbidity

5.5.2.1 Waves

Turbidity was positively correlated with wave height and wind speeds across both reefs. However, the strength of the correlations varied between reefs due to wave interactions with the coastline, and between locations on each reef due to wave interactions with reef morphology. Short period (<7 s) waves driven by locally generated winds were the main agent of resuspension given that long period swell waves (>7 s; Lou & Ridd, 1997) were rarely recorded and wave direction was consistent with local wind direction (Fig. 2). Larcombe & Costen (2001) similarly concluded that local wind was a key driver of sediment resuspension and turbidity in an earlier study at Paluma Shoals. In contrast, Orpin *et al*. (2004) found that there was a poor correlation between local wind speeds and turbidity at Nelly and Geoffrey Bay on Magnetic Island, and instead used regional wind speeds obtained from the Bureau of Meteorology. However, they had used local wind data collected from the Townsville Airport which is situated inland. In this study I used wind data collected by the AIMS weather station at the Platypus Channel which should provide a more comparable account of winds at the reefs.

5.5.2.2 Currents

Current direction at Middle Reef and Paluma Shoals agreed with previous field-based and modelling studies (Larcombe *et al*., 1995; Larcombe & Woolfe, 1999b): during the flood tide, currents moved to the NW and during the ebb tide currents moved towards the SE at Middle Reef and NE at Paluma Shoals. However, the time series data suggest that currents measured during the sampling period were too weak to resuspend sediments, and are less important drivers of turbidity than the wave climate at our study sites (Larcombe *et al*., 1995; Larcombe *et al*., 2001; Whinney, 2007). Tides and tidal currents can influence turbidity by enhancing the effect of waves and increasing the rate of sediment resuspension and turbidity (Lou & Ridd, 1997), but bottom currents at both reefs were typically <15 $cm.s^{-1}$, which are not large enough to resuspend silts and fine sands (Schoellhamer, 1995). A weak tidal signature in turbidity was observed during the spring tides when bottom current speeds were >15 $cm.s^{-1}$ and surface currents speeds reached <30 $cm.s^{-1}$. This occurred during the flood tides at Paluma Shoals and the ebb tides at Middle Reef.

5.5.3 Ecological implications

Coral assemblages at Middle Reef and Paluma Shoals were spatially distributed between geomorphological zones (e.g. windward and leeward edge) due to differences in the wave energy (Roberts *et al*., 1992) and the turbidity regime, as well as differences in the ecological responses of corals to sediment deposition and resuspension (Yamano *et al*., 2003; Anthony & Connolly, 2004). At Middle Reef, the windward edge was dominated by fast-growing *Acropora* and *Montipora* sp. typically observed in high energy environments with limited sediment deposition and low turbidity (Robert, Wilson, 1992), while the sheltered slopes of the western inner basin were dominated by *Turbinaria* and large *Porites* bombies where fine sediments were deposited and large fluctuations in turbidity were observed (Table 5.1). At Paluma Shoals, *Galaxea* was the dominant coral found to be most abundant on the leeward edge where sediment deposition was high, whereas *Goniopora* and *Turbinaria* dominated the windward edge, where extreme fluctuations in turbidity were measured (>100 NTU). Corals that dominate zones on reefs characterised by large fluctuations in turbidity, have adapted to overcome low light availability. For example, *Goniopora* and *Turbinaria* are able to feed heterotrophically thereby overcoming energy deficits due to reduced light availability (Anthony, 2000; Anthony, 2006; Sofonia, 2006). *Turbinaria* was also abundant at sites of high deposition, but is morphologically plastic which enables it to develop its characteristic funnel shape and channel sediments to a small area at the base of its skeleton, thereby reducing the area impacted by sediment smothering (Sofonia and Anthony, 2008). Despite extensive research on coral adaptations to sedimentation and turbidity, there is limited data for most coral species to establish reliable estimates of the upper turbidity thresholds (Anthony & Fabricius, 2000). Furthermore, the same coral species found at two different reefs can have different responses and upper thresholds to turbidity. Therefore, a more reliable approach is to define what constitutes as a large increase in turbidity above a site's natural turbidity regime.

Turbidity at Paluma Shoals was higher than at Middle Reef suggesting that corals at Paluma Shoals are better adapted to naturally high turbidity regimes and, therefore, are better able to cope should sediment delivery rates increase. However, if sediment delivery rates increase, it is not just turbidity that will rise, but also sedimentation, considered to be a greater threat to reef benthos than elevated turbidity (Woolfe & Larcombe, 1998). Sedimentation rates will most likely rise in the more sheltered reef habitats, such as the western basin at Middle Reef, or at deeper sites outside the wave base (Wolanski *et al*., 2005), and may be more of a threat to reef benthos within these low energy reef habitats. To determine if corals are threatened by sediments, reefs either need to be monitored regularly, or alternatively a model can be developed that predicts turbidity under various wind and wave conditions. Sustained deviations from these predictions would suggest that the natural turbidity regime had changed and corals may be threatened by increased sediment loads, both in suspension and when deposited.

5.5.4 Modelling turbidity

Previous studies have used regional forecasts of daily offshore wind speeds to predict turbidity which has been found to be a reliable and cost effective method for coarse assessments (Orpin *et al*., 2004; Whinney, 2007). A similar approach was used in this study, however, local wind data recorded near the study sites as opposed to offshore wind data were used to develop the turbidity model. This decision was taken given that locally generated winds were strongly correlated to waves and turbidity. The model successfully predicted the variance in turbidity based on 24 hour averaged wind speeds at Paluma Shoals, although at Middle Reef, 72 hour and 3-hour averaged wind speeds explained the most amount of variance in turbidity at the exposed and sheltered site respectively. Model predictions were more accurate for Paluma Shoals and for the windward reef edges due to limited wave interaction with both coastal and reef morphology. However, the weakest model at Middle Reef was still able to predict large fluctuations in turbidity and may still be effective in identifying unnaturally high turbidity levels such as those following dredging activities. The model could be improved by applying a wind direction weighting function to wind speeds to take into account variability in wind direction (Orpin *et al*., 2004; Whinney, 2007). This may improve the accuracy for the predictions at Middle Reef given that wind speeds from the N are likely to have less of an influence on turbidity. In addition, the model did not incorporate tidal movements, as they were not found to significantly improve the strength of the model, but may be necessary for regions with a greater tidal range and strong tidal currents.

These data indicate that wave exposure is the key driver of spatial variations in turbidity at both the inter- and intra-reef scale. Therefore, to accurately model turbidity specific to the reef and location on the reef, site-specific data needs to be collected. However, as demonstrated in this study, the time-frame for data collection and model development can be short (<2 weeks), so long as a range of wind and sea conditions occur within that timeframe to assess corresponding turbidity responses. Once the model is developed it can be used to plan and direct when certain activities should proceed with minimal impact to benthic communities, and can be used to determine if the frequency and severity of turbidity events is increasing at a site due to chronic increases in sediment delivery.

5.6 Conclusions

This study provides a detailed description of temporal and spatial variability in turbidity for two inshore turbid reefs on the central GBR. Middle Reef is protected by Magnetic Island within a semi-enclosed bay and Paluma Shoals is subjected to larger waves due to its exposed position. Higher wave energy at Paluma Shoals is reflected in larger fluctuations in turbidity which was 2 to 3 times greater than at Middle Reef, highlighting the spatial variation in turbidity at the scale of 10’s km. The wave climate was the most significant control on turbidity, and currents and tides were found to be less important, although a weak tidal signature in turbidity was observed during spring tides. Wave height had the largest influence on turbidity particularly at the more exposed locations on the reef where wave heights were larger, highlighting the influence of reef morphology on the relationship between wave height and turbidity.

Spatial variations in turbidity were reflected in the benthic community composition and distribution. High energy environments with smaller fluctuations in turbidity were dominated by corals such as *Acropora* and *Montipora*, whereas low energy environments with large and often prolonged turbidity peaks were dominated by heterotrophic corals such as *Goniopora, Turbinaria* and *Galaxea*. These coral community distributions will lead to spatially variable carbonate production rates and reef accretion which will in turn influence the hydrodynamic and sedimentary regimes.

Local wind speeds were strongly correlated to both wave height and turbidity, and were used to develop a turbidity model. The model was site-specific due to the high degree of spatial variability and was based on <2 weeks of 'ground truthing'. The strength of the model was greater at the more exposed reef and reef locations. These small-scale spatial differences in turbidity should be considered during site selection for long-term monitoring projects or risk management activities to maximise model reliability. Previous models developed for predicting turbidity have applied a wind direction weighting function to the wind speeds. A similar technique could be applied to this model, particularly in situations where reefs are subjected to stronger winds from a certain direction. Similarly, the model may also have to incorporate the influence of tidal movements in regions of a high tidal range and/or strong tidal movements.

6. A FIELD BASED TECHNIQUE FOR MEASURING SEDIMENT FLUX ON CORAL REEFS: APPLICATION TO TURBID ZONE REEFS ON THE GREAT BARRIER REEF

Submitted to Estuarine, Coastal and Shelf Sciences (July 2011).

Authors: N.K. Browne, S.S. Smithers, C.T. Perry, P. Ridd

6.1 Abstract

Inshore turbid reefs on the Great Barrier Reef (GBR) are exposed to relatively high and fluctuating sediment loads normally associated with poor reef growth, but many have high coral cover (>30%) and diversity (>50 species). Previous assessments of sediment regimes on these reefs have largely been based on sediment trap data which over-estimate sedimentation rates and do not accurately reflect sedimentary conditions. A new approach based on paired sediment trays is described here that allows the sedimentation rate, sediment resuspension and the total mass of mobile sediments transported on to and off a site (termed the sediment flux rate) to be measured or calculated. Sediments were collected every 4 to 6 weeks to measure seasonal differences in sedimentation, and resuspension rates were calculated by comparing 100 g of pre-analysed sediments placed on trays at deployment to sediments recovered two weeks later. The sediment trays were deployed on Middle Reef and Paluma Shoals, two inshore turbid reefs on the GBR where the sediment flux rates ranged from 35 g/m^2/day in protected reef habitats to >640 g/m^2/day on exposed reef regions. However, mean sedimentation rates (<122 g/m^2/day) were lower than previously published estimates available for nearby coral reefs, the difference due to sediment resuspension. These data demonstrate that despite high sediment delivery rates, sedimentation may still be low and potentially less of a threat to benthic communities on turbid reefs than previously assumed. Sediment trays provide a comprehensive assessment of sediment regimes, which together with ecological assessments of coral cover, improve our understanding of the sedimentary pressures affecting inshore turbid reefs, and their ability to tolerate sedimentation.

6.2 Introduction

A detailed knowledge of sediment regimes is required to understand how marine ecosystems respond to high sediment loads. Excessive sediment loads can negatively affect coastal coral reefs both as suspended load, which increases turbidity and limits light penetration to depth (Rogers 1990; Wolanski & De'ath 2005), or when it is deposited and smothers reef benthos (Loya 1976). The inshore reefs of the Great Barrier Reef (GBR) are exposed to high sediment loads (Woolfe *et al.* 1998; Wolanski *et al.* 2005; Wolanski *et al.* 2008; Devlin & Schaffelke 2009), and as such are widely perceived to be degraded systems with low coral cover and diversity (Done *et al.* 2007; Smith *et al.* 2008). Recent investigations show, however, that these inshore reefs can support diverse and distinctive coral assemblages adapted to elevated sedimentation and turbidity conditions (Veron 1995; Ayling & Ayling 1999a; Perry & Smithers 2006). Although conceptual models have been proposed to explain turbid zone reef growth and other reef types (Woolfe & Larcombe 1999; Kleypas *et al.* 2001), quantitative data documenting the sediment regime where these reefs initiate and grow are rare.

Collecting reliable and representative data on sediment regimes is difficult (Jurg 1996). Previous research has largely relied on sediment trap data, but these data can be problematic because the rate at which sediments collect in traps is reliant on trap geometry, sediment grain size and suspended sediment concentration (SSC; Gardner 1980). Sediment traps also tend to collect coarse sediments and underestimate fines, as well as overestimating sedimentation rates in high energy settings where resuspended sediments are also trapped (Jurg 1996; Thomas & Ridd 2004; Storlazzi *et al.* 2011). The balance between deposition and resuspension has major implications for coral reef health and reef accretion rates, and therefore it is important to evaluate and quantify these processes. Sediment regimes on reefs have also been examined using less commonly used techniques ranging from anchored tiles, horizon markers and changes in suspended sediment concentrations (SSC), as well as with more sophisticated instruments like sediment accumulation sensors which continuously measure sedimentation rates (Thomas & Ridd 2005) but have low spatial coverage and high cost (see Thomas & Ridd 2004 for a review).

Here I present a new methodology to better quantify sedimentation, sediment resuspension and fluxes across a coral reef. The approach is based on paired sediment trays that have been designed to reduce problems associated with sediment traps. The trays allow for sediment deposition and resuspension, and therefore assess net depositional rates which are a more accurate estimation of sedimentary processes. An experiment was designed using paired sediment trays deployed for one year on two inshore turbid reefs on the GBR that experience high and fluctuating sediment loads. On deployment, one tray was covered with a known mass of pre-analysed sediments, which were recovered two weeks later to determine shorter-term sediment resuspension rates. The total of mass of sediments both deposited and resuspended over the year, was calculated as a sediment flux rate, which represents the total mass of mobile sediments at a site. Specifically I: 1) assessed spatial and temporal differences in the rate of net sediment deposition; 2) described the nature of sediments deposited and resuspended; 3) distinguished between intra-annual depositional rates and annual sedimentation rates; and 4) quantified the total mass of mobile sediments at each site. My data reveals new insights into sediment regimes on inshore turbid reefs and demonstrates the utility of this simple but effective methodology.

6.3 Site Description

Study area and sites described in detail in section 4.3.

6.4 Materials and Methods

6.4.1 Apparatus and sediment collection

Each sediment tray array consists of two stainless steel sediment trays (35 x 20 cm) secured in an aluminium frame, which was laid flat on the substrate and stabilised with a 20 kg weight attached at one end and steel pegs at the other (Fig. 6.1). The trays are approximately 2.5 cm deep and were orientated with the shorter edge facing the prevailing water movement to reduce the interaction between the tray edge and water movement. Sediment tray arrays were deployed in September 2009 at a leeward and windward location (-1.5 to 3 m), and at a central location at each reef (0.5 m; Fig. 6.2). The number of paired trays were sufficient for inter and intra-reef replication (tested using one-way and two-way ANOVA's) whilst meeting marine permit regulations. Sediments were collected from the sediment trays *in situ* using a hand-held air-lift underwater vacuum and suctioned into a plastic container before being brought to the sea surface. Sediments were then flushed from the container into plastic bags for transport to the laboratory.

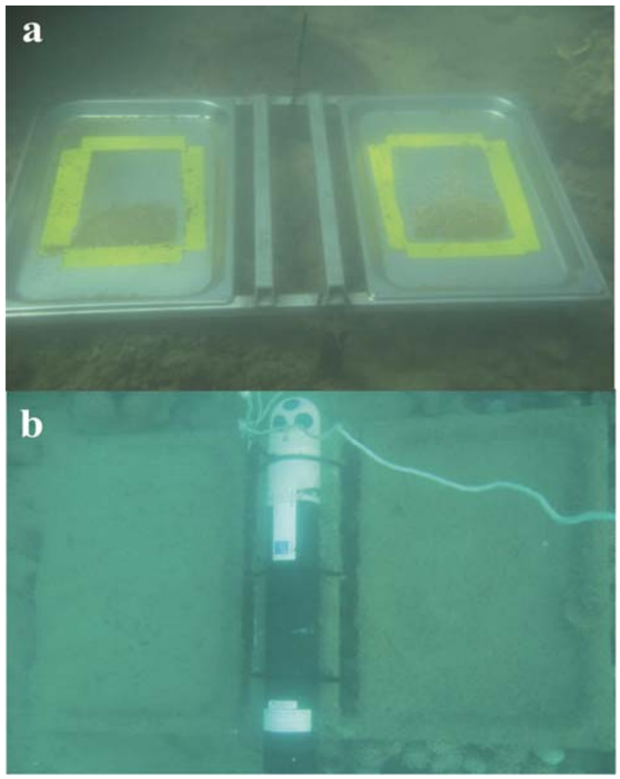

Figure 6.1: Sediment trays *in situ* (a) on deployment. Yellow tape was used to secure 100 g of sediments by a plastic sheet. The plastic sheet was removed once trays were stable. (b) ADCP attached across the centre of the tray frame to measure wave data.

6.4.2 Deployment strategy

One sediment tray on each frame was used to determine short-term or seasonal variations in net sediment deposition and shorter-term resuspension rates, and the other was used to determine long-term or annual net sediment deposition and longer-term annual resuspension rates. On deployment, 100 g of mixed sediments (approximately 50% carbonate) of known particle size distribution were placed on the seasonal tray to measure shorter-term resuspension rates, while the annual sediment tray remained clear.

The 'known' sediments were coarser (>100-1000 µm) than sediments typically deposited at each location on the reef, and had been collected from the most windward regions of each reef. Coarse sediments were used to allow the identification of finer sediments (<500 µm) deposited during a two week period as well as simultaneously assessing which particles of the original 100 g had been removed due to resuspension

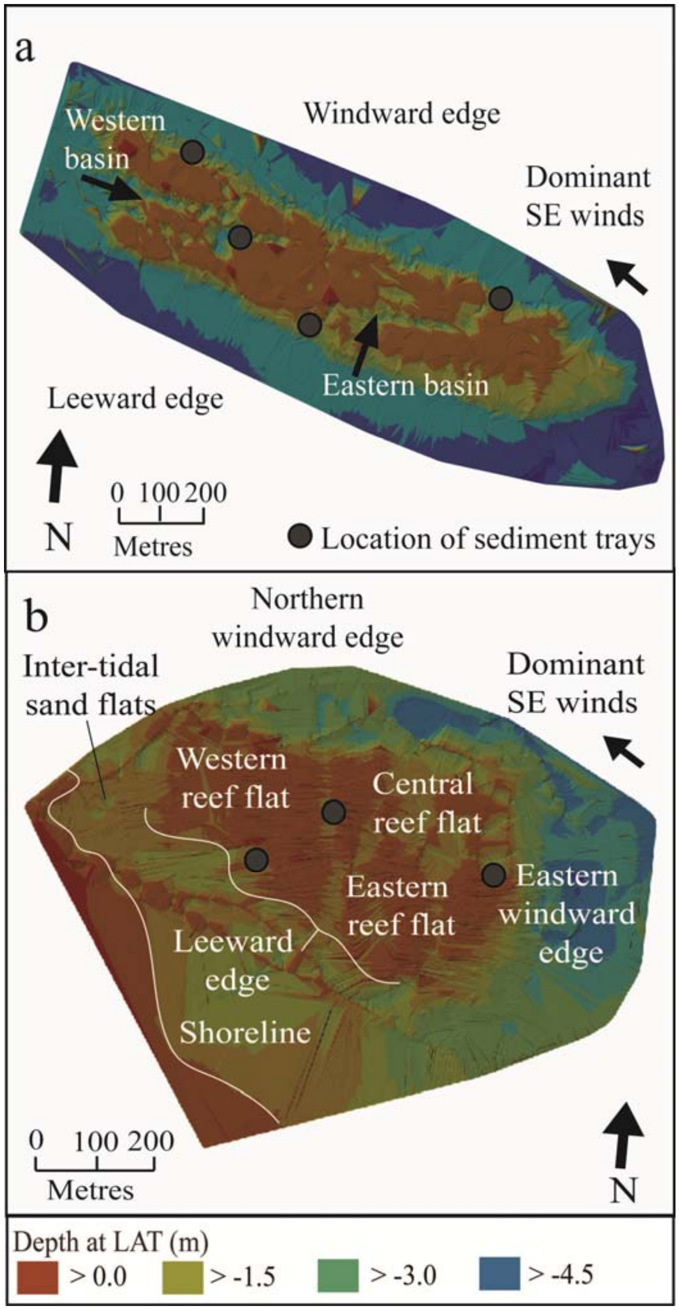

Figure 6.2: Bathymetric images of (a) Middle Reef and (b) Paluma Shoals showing the location of sediment trays on each reef.

events. However, it should be noted that the use of coarser sediments will provide a conservative estimate of resuspension rates given that the finer sediments surrounding the trays are more easily resuspended. This decision was taken to allow for the identification of an accumulation of sediments onto the trays, which had they been similar may have been misidentified as the original 100 g and reduced calculated resuspension rates. A two week timeframe was chosen as this provided a representative sample of weather and wave conditions that may resuspend sediments. Over the following year sediments deposited on the seasonal depositional tray were removed every four to six weeks, depending on weather conditions and logistical considerations, but sediments on the annual sediment tray remained untouched and were allowed to accumulate over the course of the year. Sedimentation rates were averaged across seasons, spring (September to November), summer (December to February), autumn (March to May) and winter (June to August) to accommodate variations in sampling schedules imposed by weather and safety (Table 6.1).

Table 6.1: Summary of sediment sampling schedule (S) and data logger deployment to measure turbidity (T) and wave regimes (W) at Middle Reef and Paluma Shoals over one year.

Reef	Site	2009				2010							
		Sept	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
Middle Reef	Eastern windward	S		S			W T S		W T S	S	S		S
	Western windward	W S	S	S			S		S	S	W T S	S	S
	Western central	S		S			S		W T S	S	W T S	S	S
	Leeward	W T S		S			W S			S	S		S
Paluma Shoals	Central reef flat	S	S			S				S			
	Leeward	S	W S			S			S	S	S	W T S	S
	Windward	S	W S			S			W T S	S	S	W T S	S

After one year in the field (August 2010), sediments were removed from both trays to assess and compare annual net sediment deposition and annual resuspension rates to seasonal deposition and short-term resuspension rates. The total amount of sediments remaining on the annual sediment tray was lower than the cumulative mass of sediments collected from the seasonal sediment tray due to losses associated with longer-term resuspension. Longer-term annual resuspension is not accounted for on the seasonal tray where sediments are collected every 4 to 6 weeks. The difference between the annual and seasonal depositional rate is taken as the annual resuspension rate.

6.4.3 Sedimentary regime and definitions

The key sediment regime parameters derived using the sediment trays are defined below together with a detailed description of how each was calculated.

Seasonal sedimentation rate **(D)** represents the accumulation of new sediments on to the seasonal tray over a period greater than a full lunar cycle but less than 6 weeks. During this study sediments were collected from each seasonal tray eight times (collections 2 to 9), following completion of the two-week experiment (collection 1) to measure intra-annual resuspension rates. These data reveal seasonal and event scale variations in sedimentation rate ($g/m^2/day$) and deposited sediment grain size. The mean seasonal sedimentation rate (D_S) was calculated as the average of all 8 seasonal sedimentation rates.

Seasonal resuspension rate (R_S) represents shorter-term frequent resuspension events and is derived from the re-analysis of grain size distributions of sediments collected (collection 1) from the seasonal tray after it was dosed with 100 g sediment of known texture and left in the field for two weeks. This procedure took place in September 2009 when daily average wind speeds ranged between 10 to 30 $km.hr^{-1}$, and were predominantly from the SE. The first step is to determine the resuspension fraction (R_{FS}), which represents the percentage of the original dosed sediments that have been resuspended, by comparing the particle size distribution curves of the collected and original 'known' sediments. The seasonal resuspension rate ($g/m^2/day$) was then calculated by multiplying the seasonal deposition rate (D_S) by the seasonal resuspension fraction (Eq. 1)

$$R_S = [D_S/(100-R_{FS})] \times R_{FS} \qquad \textit{Equation 1}$$

Net annual sediment deposition rate (D_A) is the net sediment deposition over one year, and was determined from the one off collection of sediments from the annual sediment depositional tray (g/m^2/day).

Annual resuspension rate (R_A) represents resuspension events that occur over longer timeframes on the annual sedimentation tray (g/m^2/day). The annual resuspension rate is calculated by firstly determining the percentage difference between the mean seasonal depositional rate and the annual depositional rate. The percentage or fraction calculated represents the additional mass of sediments that have been resuspended from the annual sediment tray (R_{FA}; Eq.2).

$$R_{FA} = 100 - [(D_A/D_S) \times 100] \qquad \textit{Equation 2}$$

The annual resuspension rate (R_A) is then calculated by multiplying the net annual deposition rate by the annual resuspension fraction (R_{FL}; Eq. 3)

$$R_A = [D_A/(100-R_{FA})] \times R_{FA} \qquad \textit{Equation 3}$$

Sediment flux rate (F) describes the total mass of sediment that has been deposited and resuspended at a site (g/m^2/day) and provides an indication of how much sediment is moving through each site. It is calculated as the total mass of sediments that have been deposited and resuspended following both short- and longer-term resuspension events (Eq. 4).

$$F = (R_S + R_A) \qquad \textit{Equation 4}$$

6.4.4 Particle size analysis

Sediments were dried at 55^{0}C for 24 to 48 hours, weighed (to the nearest 0.001 g) and analysed for particle size distribution. Particle size was determined using a Malvern Mastersizer-X laser particle sizer for fine sediments and a Rapid Sediment Analyser (RSA) settling tube for the coarser sediment fraction as described in section 4.3.7.

6.4.5 Hydrodynamics

Wind-driven waves are the dominant control of sedimentary regimes on the inner GBR (Lou & Ridd 1997; Orpin *et al.* 2004). Half-hourly wind data for Cleveland Bay is collected by the Australian Institute of Marine Science (AIMS) weather station on the S5 Platypus shipping channel marker (Fig. 1.1). Wave measurements were collected using a Nortek 2 MHz Acoustic Doppler Current Profiler (ADCP) as described in section 4.3.4. ADCPs were carefully mounted on to the aluminium frame, in between the two sediment trays (Fig. 6.1b). In this position they present minimum disturbance to water flow over the sediment trays. ADCPs were deployed for up to two weeks, and two deployments were carried out at each location on the reef (Table 6.1). ADCPs were not deployed on the reef flat at Paluma Shoals because risk of physical damage or loss of the instrument was considered to be high.

6.4.6 Turbidity

Spatial and temporal variations in turbidity were examined. Turbidity data was collected simultaneously with wave data using nephelometers (as described in section 5.3.2) to identify wind and wave conditions that could potentially resuspend sediments and increase turbidity (Table 6.1). Instruments were deployed for up to two weeks to capture turbidity events during the different seasons. Instruments could not be deployed at every location on the reef in every season due to cost and the number of instruments available.

6.5 Results

6.5.1 Seasonal sedimentation rates

Sedimentation rates varied significantly over Middle Reef ($F_{(3,22)} = 4.46$, $p=0.014$) and Paluma Shoals ($F_{(2,22)} = 5.54$, $p=0.012$), with lowest mean sedimentation rates occurring on the leeward edge at Middle Reef (29.8 $g/m^2/day$) and on the reef flat at Paluma Shoals (0.9 $g/m^2/day$), and highest rates of sedimentation occurring within the sheltered western central regions at Middle Reef (73.7 $g/m^2/day$) and the protected leeward edge at Paluma Shoals (121.6 $g/m^2/day$; Table 6.2). However, there was no

Table 6.2: Site descriptions and seasonal variations in sedimentation rates for each reef site together with calculations for mean seasonal (D_S) and annual sediment deposition rates (D_A), resuspension rates (R) and sediment flux rates (F)

REEF	Middle Reef				Paluma Shoals		
Site description	Eastern windward	Western windward	Western central	Leeward	Windward	Reef flat	Leeward
Exposure to waves	High	Medium	Low	Medium to low	High	High	Low
Depth (m) at LAT	-3	-3	-3	-2	-2.5	0.5	-1.5
Hard coral cover (%)	82	60	27	51	31	23	39
Dominant corals	*Acropora Montipora*	*Goniopora Acropora*	*Montipora Acropora Turbinaria Pachyseris*	*Goniopora Acropora*	*Turbinaria Acropora Montipora*	*Goniastrea Platygyra Porites*	*Galaxea Goniastrea Porites*
SEDIMENT DYNAMICS							
Dominant sediment mode (µm)	350-710	90-400	30-150	20 -90	50-250	710-1200	10 - 90
Sediment description	Medium to coarse sands	Very fine to medium sands	Medium silt to fine sand	Medium to very coarse silt	Coarse silt to medium sand	Coarse sand to very fine gravel	Medium to very coarse silt
Sedimentation rate ($g/m^2/day$)							
Spring	0.0	51.4	98.6	29.1	0.0	0.9	62.6
Summer	27.4	1.3	72.0	8.6	2.8	1.5	14.0
Autumn	78.2	39.8	109.5	30.0	13.4	1.2	85.8
Winter	61.0	42.9	14.8	51.4	26.4	0.0	324.1
Mean sedimentation rate ($g/m^2/day$) (D_S)	41.7	33.8	73.7	29.8	10.6	0.9	121.6
Net annual sediment deposition ($g/m^2/day$) (D_A)	23.3	8.1	62.1	4.7	0.0	0.0	44.1
ST sediment resuspension function (%) (R_{FS})	94	20	27	73	79	87	67
ST sediment resuspension rate ($g/m^2/day$) (R_S)	625	9	27	80	40	6	251
LT sediment resuspension function (%) (R_{FA})	44	76	16	84	100	100	64
LT sediment resuspension rate ($g/m^2/day$) (R_A)	18	26	12	25			77
Sediment flux rate ($g/m^2/day$ (F)	643	34	38	105			329

significant difference in sedimentation rates between Middle Reef and Paluma Shoals ($F_{(1,48)} = 0.06$, $p=0.82$).

Sedimentation rates also varied between seasons at each tray location with a significant difference between summer and Autumn at Middle Reef ($F_{(9,10)} = 10.8$, $p=0.0$) and at Paluma Shoals ($F_{(6,12)} = 2.3$, $p=0.1$). In general sedimentation rates were consistently lower than the mean in summer and higher in autumn and/or winter (Fig. 6.3). Sedimentation rates in summer were typically <30 g/m^2/day, with the exception of the western central basin at Middle Reef, and increased in autumn to >30 g/m^2/day at Middle Reef, with >80 g/m^2/day measured in the western central basin and on the leeward edge at Paluma Shoals. In winter, sedimentation rates ranged from 15 to 65 g/m^2/day at Middle Reef, although the highest sedimentation rate occurred on the leeward edge at Paluma Shoals (324 g/m^2/day). In spring sedimentation rates remained high (>50 g/m^2/day) within the sheltered regions of each reef such as the western central basin at Middle Reef and the leeward edge at Paluma Shoals, but fell to < 1 g/m^2/day in the exposed windward regions and reef flats at both reef sites.

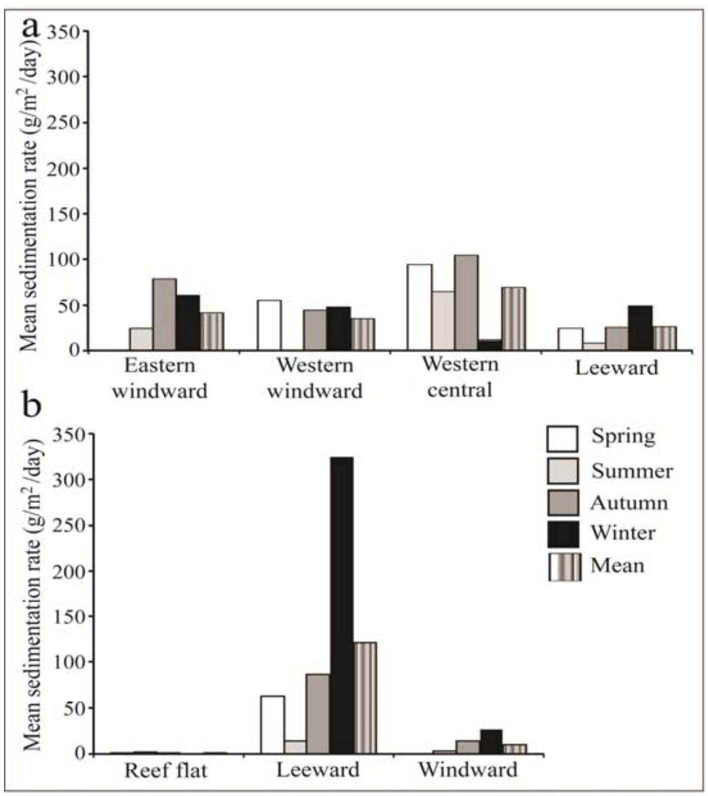

Figure 6.3: Seasonal variations in sedimentation rates and the mean annual sedimentation rate at (a) Middle Reef and (b) Paluma Shoals.

6.5.2 Particle size distribution

At Middle Reef sediment texture generally fined from E to W with medium to coarse sands (350 to 710 µm) deposited on the eastern windward edge, very fine to medium sands on the western windward edge (90-400 µm), medium silts to fine sands within the western central basin (30-150 µm), and medium to coarse silts (20 to 90 µm) deposited on the leeward edge (Table 6.2). There was little change in sediment texture in spring and summer on each tray but there was an influx of coarse silts to fine sands onto the eastern windward edge and the leeward edge in autumn, and onto the western central and windward locations in winter (Fig. 6.4). At Paluma Shoals, coarse to very coarse sands (710 to 1200 µm) dominated the reef flat, very fine to coarse sands (100 to 700 µm) dominated the windward edge, and fine to coarse silts (10 to 90 µm) dominated the leeward edge (Table 6.2). The texture of reef flat sediments varied little throughout the survey period (Fig. 6.4). However, at the leeward edge medium to coarse sands were deposited in spring and very fine to coarse silts in summer. Mainly very fine to coarse silts were deposited along the windward edge throughout most of the year, except in winter when very fine to medium sands were more common.

6.5.3 Seasonal sediment resuspension

At Middle Reef the grain size of sediments resuspended from the trays varied over the reef. On the eastern windward edge approximately 94% (R_{FS}) of very fine silts to very fine pebbles (Fig. 6.5a) were resuspended, which equated to a resuspension rate of 625 $g/m^2/day$. At the western windward edge only 20% of sediments (fine to very coarse sands) were resuspended at a rate of 9 $g/m^2/day$, and silts to very fine sands were deposited (Fig. 6.5b). The sediment resuspension fraction (27%) and rate (27 $g/m^2/day$) were marginally greater in the western central basin where resuspended sediments consisted of medium sands to very fine pebbles, and deposited sediments ranged from silts to very fine sands (Fig. 6.5c). The sediment resuspension fraction increased to 73% on the leeward edge (very fine to very coarse sands), however, as the mean sedimentation rate was low (30 $g/m^2/day$), the sediment resuspension rate (80 $g/m^2/day$) was comparable to the western central basin (Fig. 6.5d).

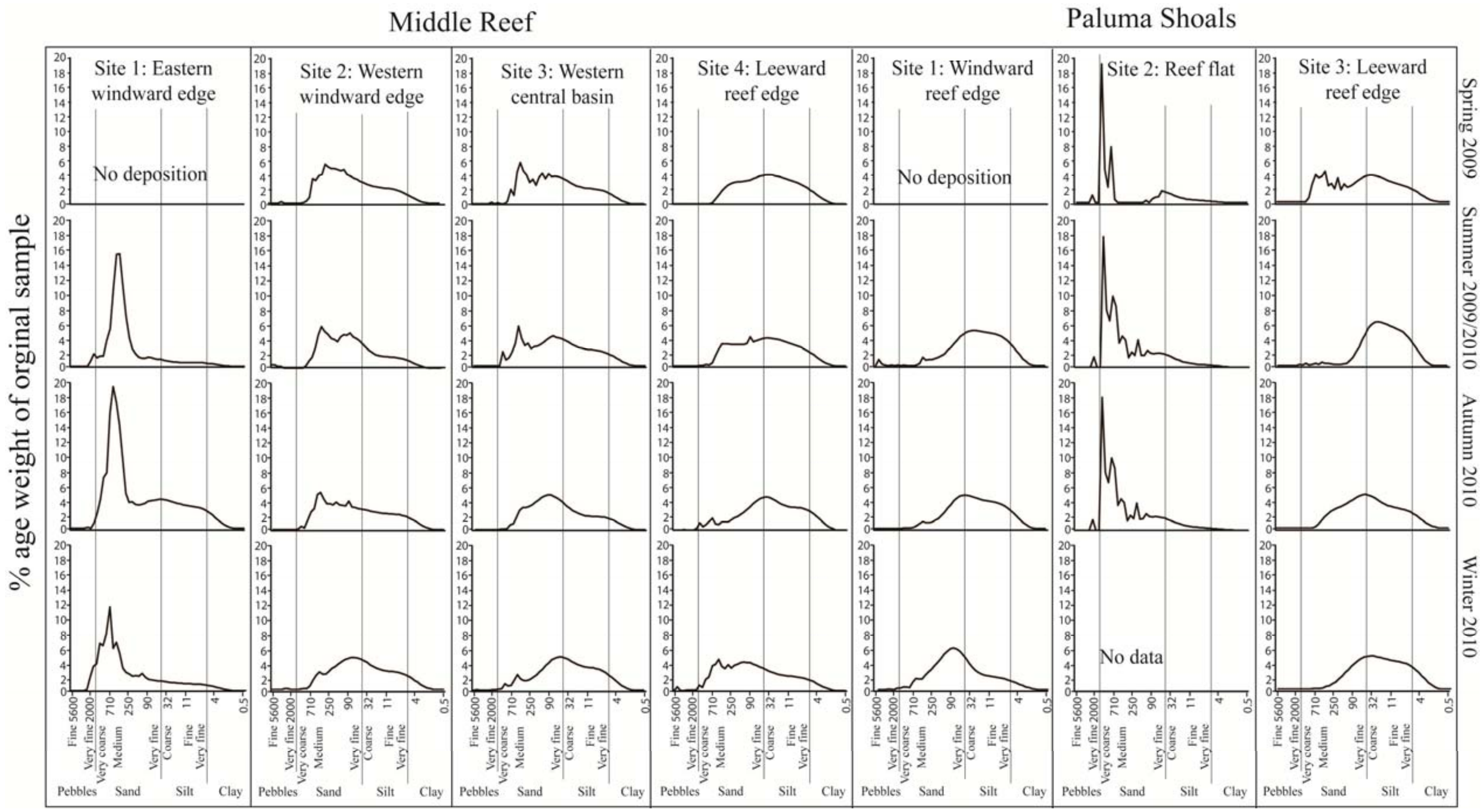

Figure 6.4: The mean particle size distribution of sediments collected every 4 to 6 weeks to give the seasonal average for spring, summer, autumn and winter.

At Paluma Shoals, 87% of sediments (silts to very coarse sands) on the reef flat have been winnowed away at a rate of 6 g/m^2/day, with limited additional deposition of fine sediments, resulting in the accumulation of very fine pebbles (Fig. 6.5e). In contrast, 100% of very coarse sands and approximately 80% of medium sands were resuspended on the leeward and windward edge, and a large amount of silts and very fine sands were deposited (Fig. 6.5 f & g). However, the resuspension rate varied between the windward (40 g/m^2/day) and leeward edge (251 g/m^2/day) due to differences in the mean sedimentation rate.

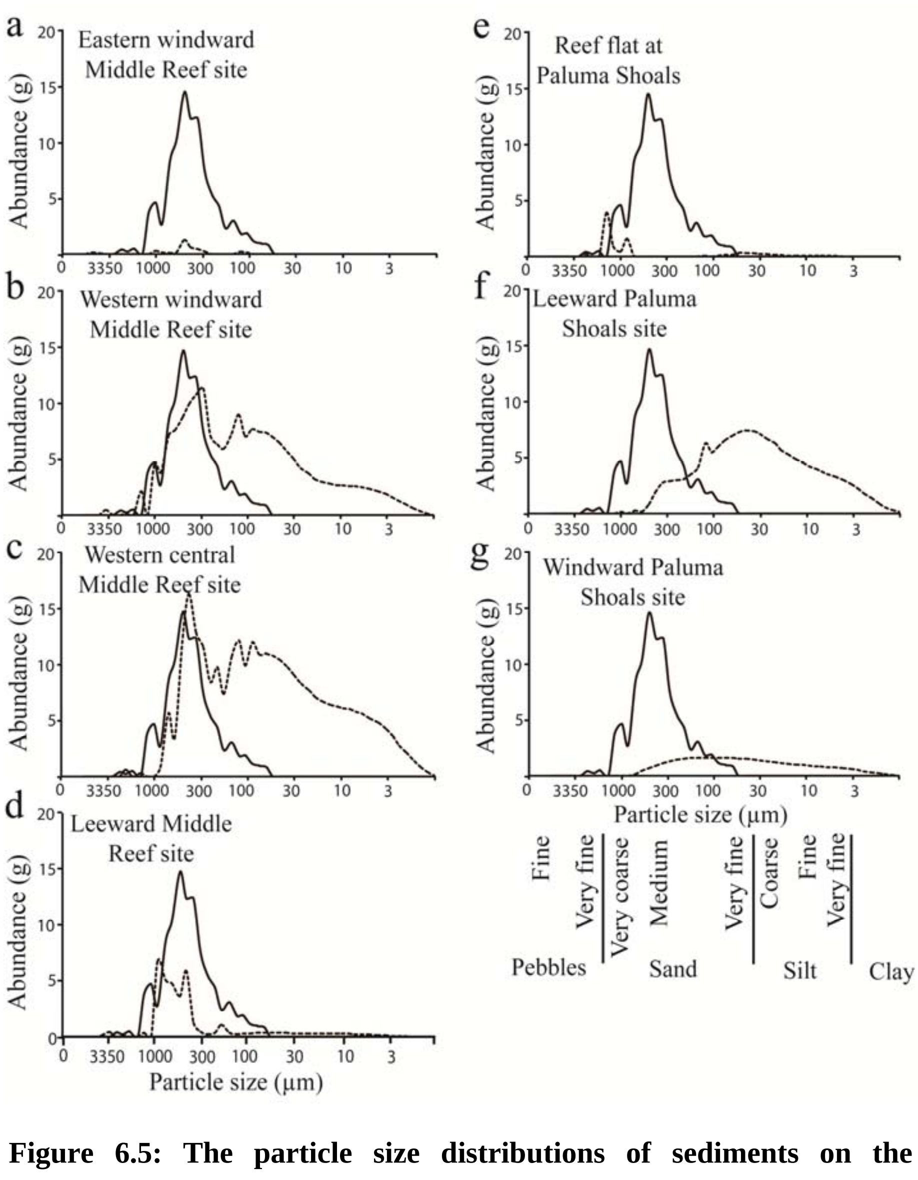

Figure 6.5: The particle size distributions of sediments on the seasonal depositional tray before (continuous black line) and after (dashed line) two weeks in the field.

6.5.4 Net annual sediment deposition and resuspension rates

Sediment deposition on the net annual depositional tray following twelve months in the field was consistently lower (D_A) than the mean seasonal sediment depositional rate at all tray locations on both reefs (D_S; Table 6.2). On the eastern windward edge of Middle Reef, 23.3 g/m^2/day were deposited on the annual depositional tray compared to an average rate of 41.7 g/m^2/day on the seasonal depositional tray. These data suggest that over the year, an additional 44% of sediments (R_{FA}), originally deposited and accumulated following seasonal resuspension events, were resuspended at a rate of 18 g/m^2/day and removed in the long-term (Table 6.2). Particle distribution curves of the sediments collected from the net annual depositional tray and the sum of all sediments collected from the seasonal depositional tray over the year, indicated that very fine to coarse sands were preferentially re-suspended and redistributed (Fig. 6.6a). On the western windward edge, the net annual sediment deposition was 8.1 g/m^2/day indicating that longer-term annual resuspension removed 76% of sediments at a rate of 26 g/m^2/day. However, particle distribution curves of sediments on both trays were similar suggesting that all sediment sizes were being resuspended to some degree (Fig. 6.6b).

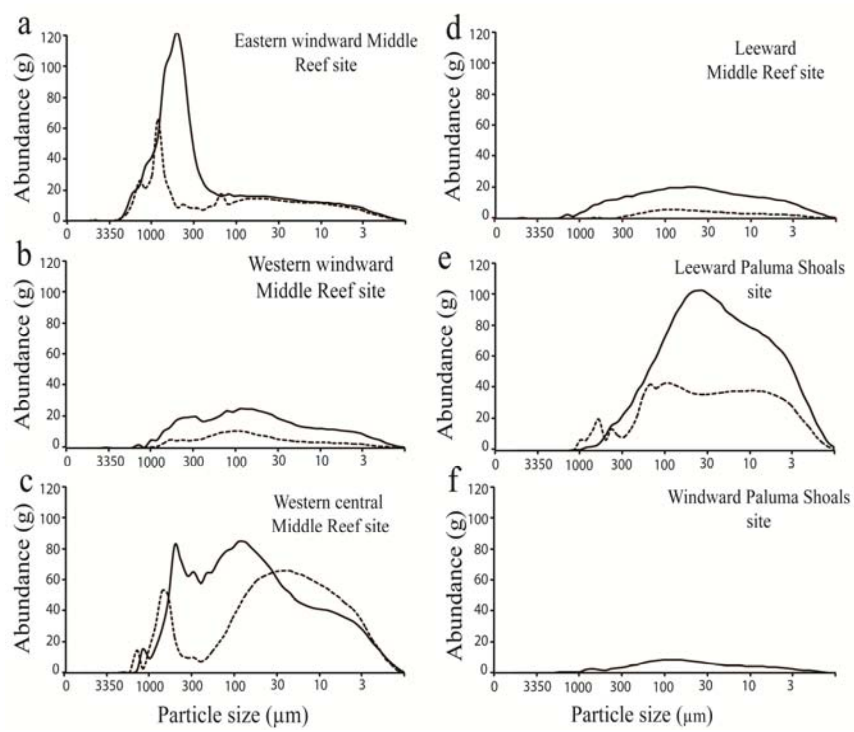

Figure 6.6: The difference in the particle size distribution between the gross sediment deposited on seasonal depositional tray and the sediment accumulated on net annual accumulation tray.

In the western central basin the net annual sediment deposition rate was 62.1 $g/m^2/day$ and only 16% of deposited sediments, consisting of very fine to medium sediments, were resuspended at a rate of 12 $g/m^2/day$ (Fig. 6.6c). In contrast, the leeward edge had a low net annual sediment deposition (4.7 $g/m^2/day$) and a high sediment resuspension rate (25 $g/m^2/day$; Fig. 6.6d). At Paluma Shoals, a net annual sediment deposition rate was limited to the leeward edge (44.1 $g/m^2/day$) as no sediments had accumulated on the reef flat and windward net annual deposition tray (Table 6.2). Annual resuspension rates could, therefore, only be calculated from the leeward edge, where 64% of sediments, consisting of silts to medium sands, were resuspended at a rate of 77 $g/m^2/day$ (Fig. 6.6e & f).

6.5.5 Sediment flux rates

At Middle Reef, the highest sediment flux rate occurred at the exposed eastern windward edge (643 $g/m^2/day$), and lowest along the western windward reef edge (34 $g/m^2/day$). At Paluma Shoals, the sediment flux rate could only be calculated for the leeward edge (329 $g/m^2/day$) as the annual resuspension rate was 100% on the reef flat and windward edge, and therefore represents an unknown quantity.

6.5.6 Wind regime

Daily dominant winds measured at the AIMS weather station in Cleveland Bay during the survey period (Sept 2009 to August 2010) blew from the NE for 39 days, from the E for 110 days, from the SE for 128 days, and from the S for 63 days. Wind direction and speed varied seasonally (Fig. 6.7). In spring (September – November 2009) wind speeds up to 30 $km.hr^{-1}$ from the NE to the SE were interspersed with winds from the NW to SW. In the summer (December 2009 – February 2010) wind speeds were moderate to very strong (10 to 40 $km.hr^{-1}$) and fluctuated between the NE to SE. Very strong winds occurred at the start of autumn (10 days in March with >30 $km.hr^{-1}$ average wind speeds), but winds speeds abated in April and May to <25 $km.hr^{-1}$ and were typically from the SE. In winter (June – August 2010) the wind blew

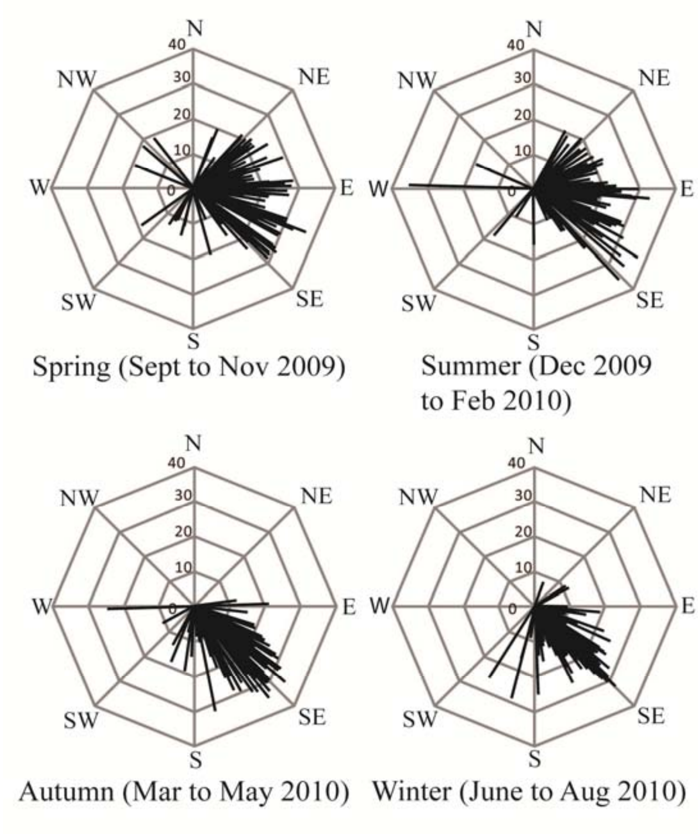

Figure 6.7: Wind rose indicating wind speed ($km.hr^{-1}$) and direction for each season during the survey period.

consistently from the SE but varied in strength from calm to strong (5 to 30 $km.hr^{-1}$) (Fig. 6.7).

6.5.7 Turbidity regime

Turbidity responses to wind-driven waves varied spatially over Middle Reef. Turbidity along the eastern windward edge was measured in late summer (17 – 25 February 2010) when moderate to strong winds (10 to 40 $km.hr^{-1}$) fluctuated between the SE to the NE (Fig. 6.8a). Turbidity was low (<2 NTU) until NE winds >25 $km.hr^{-1}$ occurred (19 February) raising wave heights above 0.8 m. At this time, turbidity rose sharply to >15 NTU for a couple of hours, before falling to ~ 5 NTU for the rest of the day and finally returning to <2 NTU the following day. Turbidity at the western windward and central locations was measured in mid winter (12 to 22 June 2010) when calm to strong winds

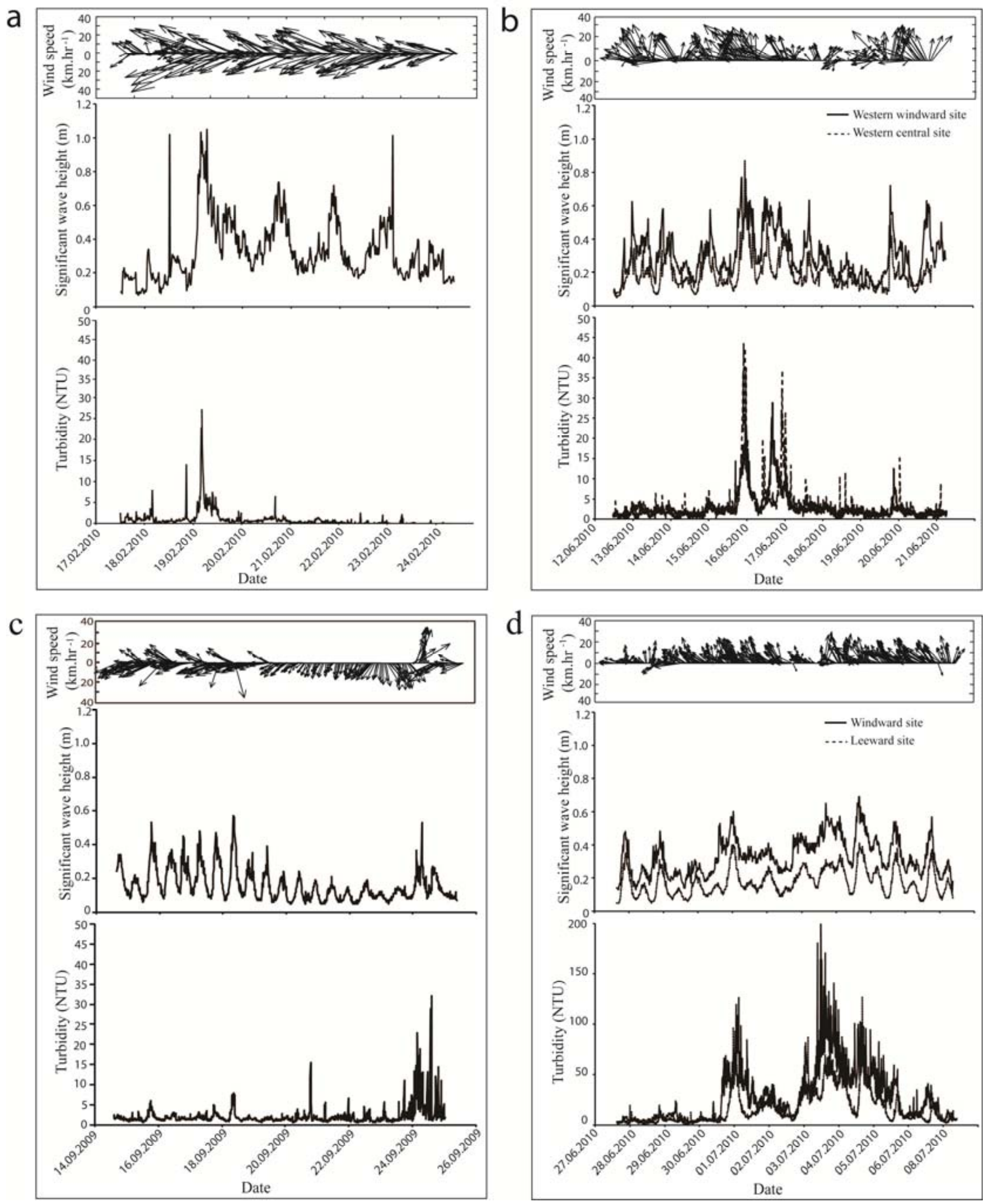

Figure 6.8: Wind, wave and turbidity data for Middle Reef and Paluma Shoals (a) data collected at the eastern windward Middle Reef site in February 2010, (b) data collected at the western windward and central sites at Middle Reef in June 2010, (c) data collected at the leeward Middle Reef site in September 2009, and, (d) data collected at Paluma Shoals in July 2010. Note different turbidity scale at Paluma Shoals.

(5 to 20 km.hr^{-1}) blew from the S interspersed with moderate to strong winds from the SE (10 to 30 km.hr^{-1}; Fig. 6.8b). Turbidity was low at both locations (<5 NTU) until strong SE winds (>30 km.hr^{-1}) occurred on the 16th June which increased turbidity to >20 NTU on the western windward edge where wave heights reached above 0.6 m, and >40 NTU in western central basin, despite lower wave heights of 0.5 to 0.6 m. Turbidity on the leeward edge was measured in spring (14 to 26th September 2009) when moderate (<15 km.hr^{-1}) NE winds were interspersed with periods of calmer northerly winds (<10 km.hr^{-1}; Fig. 6.8c). Turbidity was typically <3 NTU, only increasing to >10 NTU following a few hours of strong S winds (>20 km.hr^{-1}). After the initial increase in turbidity, turbidity remained at >10 NTU for approximately 24 hours despite the relatively rapid fall in winds speed (30 to 15 km.hr^{-1}) and wave heights (>0.4 m to <0.3 m; Fig. 6.8c).

Turbidity was measured at the leeward and windward edge of Paluma Shoals in winter (29th June to 9th July 2010) when wind speeds ranged from 10 to 30 km.hr^{-1} from the E to S (Fig. 6.8d). Turbidity was low during calm wind-speeds (<10 km.hr^{-1}), but increased at both locations (>100 NTU) when wind speeds increased to >20 km.hr^{-1}. However, turbidity responses were greater along the windward edge (>200 NTU) than on the leeward edge (>100 NTU) due to higher wave heights (>0.6 m).

6.6 Discussion

6.6.1 Seasonal sedimentation rates

The sedimentation rates calculated here for Middle Reef and Paluma Shoals are markedly lower than previously reported for inshore turbid reefs on the GBR (Table 6.3). At Middle Reef mean sedimentation rates varied between 30 to 74 g/m^2/day and at Paluma Shoals rates ranged from <1 to 122 g/m^2/day (Table 6.2). Sediment trap data from Middle Reef collected prior to, during and following the dredging of the Platypus Channel in 1993 measured sedimentation rates of 270 g/m^2/day prior to dredging, and rates >600 g/m^2/day immediately after dredging ceased. Sedimentation rates between 26 g/m^2/day and 3,640 g/m^2/day have also been reported using sediment traps on the nearby fringing reefs of Magnetic Island (Mapstone *et al.* 1992), and sedimentation

Table 6.3: A review of sedimentation rates from studies in Australia, North America, Africa and Asia. Rates have also been converted to $g/m^2/day$ for comparative analysis.

Continent	Country	Reef	Site description	Rates	$g/m^2/$ day	Reference
Australia	GBR, Australia	Middle Reef	Nearshore patch reef		30 to 74	This study
		Paluma Shoals	Nearshore shoal		1 to 122	This study
		Magnetic Island	Fringing reef	0.05 to 7 g dry weight/day	26 to 3640	Mapstone, 1992
		High Island	Inner-shelf coral fringed island	2000 $mg/cm^2/year$	54.8	Wolanski & Fabricius 2005
		Magnetic Island	Fringing reef	12 $mg/cm^2/day$	120	Sofonia & Anthony 2008
		Offshore lugger shoals	Inshore shallow turbid reef	120 $g/m^2/day$	120	Wolanski *et al.*, 2008
		Dunk Island	Fringing reef	>340 $g/m^2/day$	>340	
Northern America	Hawaii	Kaneohe Bay	Lagoon slope at <6 m on reefs subjected to severe stress and runoff	34-41 $mg/cm^2/day$.	340 to 410	Maragos 1972
	Puerto Rico	Complex of reefs (~25 km^2)	High coral cover area (79%)	3 $mg/cm^2/day$	30	Loya 1976
			Low coral cover area (30%)	15 $mg/cm^2/day$	150	
	Puerto Rico	San Cristobal	0.5 m above the substratum	2-3 $mg/cm^2/day$	20 to 30	Rogers 1983
			0.1 m above the substratum	9.6 $mg/cm^2/day$	96	
	St Croix, US Virgin Islands	Cane Bay	Fringing reef	1-2 $mg/cm^2/day$	10 to 20	Gleason1998
		Salt River	Submarine canyon	4 $mg/cm^2/day$	40	
	Jamaica	Discovery Bay	Lagoon reefs	4-8 $mg/cm^2/day$	40 to 80	Macdonald & Perry 2003
	Florida, USA	Biscayne Bay	Shallow, tropical lagoon adjacent to Miami city.	100 to 600 $mg/cm^2/day$	1000 to 6000	Lirman *et al.*, 2003
			Less impacted site	50 to 150 $mg/cm^2/day$	500 to 1500	
	St. Lucia, Caribbean		Sediment exposed reef	1-4 $mg/cm^2/day$	10 to 40	Nuges & Roberts 2003
Africa	South Africa	Maputa coastline, northern Natal	Reef top coral community	16.8 $mg/cm^2/day$	168	Riegl *et al.* 1995
			Gully community	43.2 $mg/cm^2/day$	432	
	Kenya	Malindi	Series of near-shore reef platforms	3 to 4 $mg/cm^2/day$	30 to 40	McClanahan & Obura 1997

Table 6.3 cont.

Continent	Country	Reef	Site description	Rates	g/m^2/ day	Reference
Africa	Northern Gulf of Suez	Beer Odeeb	Six months after dredging	20 to 25 mg/cm^2/day	200 to 250	Ebeid *et al.*, 2009
			Ten months after dredging	10 to 12 mg/cm^2/day	100 to 120	
Asia	Singapore	Cyrene Reef	Mostly submerged patch reef ~3 km offshore	14.64 mg/cm^2/day	146.4	Low & Chou 1994
		Palua Hantu	Fringing reef ~7 km offshore	9.9 mg/cm^2/day	99	
		Raffles Lighthouse	Fringing reef ~15 km offshore	7.5 mg/cm^2/day	75	
	South Thailand	South-east coast of Phuket	Inner parts of the reef flat	16 kg/m^2/month	516	Scoffin *et al.* 1997
			Outer parts of the reef flat	13 kg/m^2/month	420	
	Indonesia	Bondo	Polluted reef	38.5 mg/cm^2/day	385	Edinger *et al.* 2000
		Palua Kecil	Pristine reef	2.8 to 4.2 mg/cm^2/day	28 to 42	
	Sulawesi, Indonesia	Fringing reefs near Hoga Island	Highly anthropogenically impacted site.	~20 g/m^2/day	~20	Crabbe & Smith 2005
			Less anthropogenically impacted site	~5 g/m^2/day	~5	
	Philippines	Bush Island	1.7 km offshore (Dry to wet season)	3 to 11 mg/cm^2/day	30 to 110	Becira 2009
		Meara Island	3 km offshore (Dry to wet season)	4 to 9 mg/cm^2/day	40 to 90	

rates of ~120 g/m^2/day have been estimated just offshore of Lugger shoals, an inshore reef located 130 km north of Paluma Shoals (Wolanski *et al.* 2008). I believe that the higher sedimentation rates reported in these earlier studies are an artefact of the sediment trap methodology. Sediment traps modify natural hydrodynamics and do not allow for resuspension, factors which both result in higher depositional rates (Thomas & Ridd 2004; Thomas & Ridd 2005; Storlazzi *et al.* 2011). In contrast, sediment trays have been designed to reduce hydrodynamic interference and allow sediments to be transported onto and off the receiving surface, thus providing a more accurate assessment of the natural sedimentary regime. The ability to distinguish between net sedimentation and resuspension is critical to understanding the sedimentary conditions that reef organisms are exposed to, particularly given that the negative impacts of deposited sediments are often argued to be greater than those associated with suspended sediment concentrations (Woolfe & Larcombe 1999).

Sedimentation rates during the wet, summer months were typically lower at Middle Reef and Paluma Shoals than during the dry autumn and winter months, although previous investigations have reported the converse due to increased sediment delivery to the coast from flood plumes during the wet season. For example, in the 2007 wet season, persistently high sedimentation rates of >340 $g/m^2/day$ were recorded on the leeward sides of Dunk and Bedarra Island situated approximately 10 km from the Tully River (delivers ~130,000 tonnes of sediments per year; Furnas 2003) and 140 km north of Paluma Shoals (Wolanski *et al.* 2008). Sediment delivery to Middle Reef from river runoff (Burdekin River, Ross River, Alligator Creek) into Cleveland Bay is estimated to be 62,400 tonnes annually (Lambrechts *et al.* 2010), the majority of which would have been delivered to Cleveland Bay during the wet summer months (>500 mm/month rainfall in January 2010; Bureau of Meteorology). This sediment delivery rate equates to approximately half that from the Tully River, however, summer sedimentation rates at Middle Reef (1 to 72 $g/m^2/day$) were far less than half the sedimentation rates at Dunk and Bedarra Island. Sedimentation rates remained low at Middle Reef due to strong NE to SE winds (>20 $km.hr^{-1}$; Fig. 6.7) which typically raise wave heights to above 0.6 m (Fig. 6.8), and have kept sediments in suspension. These data further indicate that the net sedimentation rate on these systems is far lower than previous estimates based on sediment traps particularly during high sediment delivery and flow conditions when sediment resuspension rates are high.

At Middle Reef and Paluma Shoals, the mean grain size deposited varied over the reef due to spatial variations in wave energy with coarser sediments deposited on windward locations, and fine sediments deposited on protected leeward edges and inner basins. Similarly, variations in grain size between seasons followed changes in wind and wave conditions. In autumn fine silts and sands were deposited on Middle Reef's windward edge when SE wind speeds dropped to <20 $km.hr^{-1}$, and in spring, medium to coarse sands were deposited on the leeward edge at Paluma Shoals when NE to SE winds of >20 $km.hr^{-1}$ occurred. It is important to consider the size of sediments delivered together with sedimentation rates given that since European settlement, the delivery of fine sediments to inshore regions has increased (McCulloch *et al.* 2003; Lewis *et al.*

2007), and if associated with nutrients form ‘marine snow’ which can have increased detrimental effects on reef benthos (Fabricius & Wolanski 2000). Reef habitats dominated by fine sediment deposition may be more threatened by both higher sedimentation rates, but also increased nutrient concentrations. Similar analysis is not possible with sediment traps as they have a tendency to preferentially collect larger particles (Storlazzi *et al.* 2011).

6.6.2 Seasonal sediment resuspension

Seasonal resuspension rates at Middle Reef and Paluma Shoals reflected spatial differences in sediment composition and hydrodynamics between reef locations. At Middle Reef, the proportion of sediments resuspended (94%) and the resuspension rate (625 g/m^2/day) were greatest on the exposed eastern windward reef edge where silts and fine sands were winnowed away leaving medium to coarse sands. These coarser sediments were less easily resuspended, and, as such, turbidity was low and stable, only rising to 10 to 20 NTU when wave heights were above 1 m. In contrast, the proportion (27%) and rate of sediments (27 g/m^2/day) resuspended within the western central basin was low due to lower wave activity. However, sediments in the western central basin are dominated by fine silts and sands which are rapidly resuspended and produce large fluctuations in turbidity (>30 NTU). Here, corals must withstand short periods (<6 hrs) of low light penetration and, as suspended sediments settle, they may also have to expend energy removing sediment particles from their surfaces.

At Paluma Shoals, the proportion of sediments resuspended was >67% across the reef reflecting the exposed reef location. Highest sediment resuspension rates (251 g/m^2/day) occurred on the leeward edge where sediment depositional rates were also high. In reef habitats where large quantities of fine sediments are deposited and rapidly resuspended (>100 NTU), corals must cope with both extended periods of low light (<24 hrs) and sediment burial. These spatial variations in sediment resuspension and turbidity data provide a comprehensive assessment of suspended sediment regimes between reef locations, which together with coral community descriptions can be used to determine coral tolerance thresholds to sedimentary pressures.

Sediment trays and the sampling design as employed here provide an improved assessment of both net sedimentation and shorter-term seasonal resuspension rates within a terrigenous and carbonate sedimentary setting. During the course of the experiment, however, we recognised that there were potential sources of error with regards to both the sediment tray design and survey protocol which need to be considered. The sediment trays allow for sediment resuspension, but the depth of the trays (2.5 cm), which may also change as sediments accumulate, and the aluminium frame may have some impact on the local hydrodynamics, and potentially reduce resuspension rates. Furthermore, the experimental design used to quantify resuspension rates from sediment trays is somewhat dependent on both location characteristics (e.g. sediment type and hydrodynamics) and research objectives. In this study, resuspension rates were assessed during a two-week period at the start of deployment using 100 g of sediments collected from the reef. Two weeks provided an adequate time frame in which to capture typical wind and wave conditions (i.e. not extreme weather conditions), and assess sediment responses. This one-off measurement was taken as a proxy for shorter-term seasonal sedimentation rates over the course of the year, however, the authors recognise that the assessment of shorter-term seasonal resuspension rates can be improved by increasing the frequency of measurements. In addition, the time frame can be lengthened or shortened depending on local sedimentary and hydrodynamic conditions. For example, resuspension rates could be measured over a 24 hour period and compared on a weekly basis to provide a fine-scale assessment of sediment processes in highly dynamic sedimentary settings. In summary, the sediment trays provide a conservative proxy for shorter-term seasonal sediment resuspension rates, which cannot be obtained from sediment traps, and the design approach can be modified to meet local considerations and user needs.

6.6.3 Net annual sediment deposition and resuspension rates

Net annual sediment deposition rates on Middle Reef and Paluma Shoals were low (<62 $g/m^2/day$) and suggest that sedimentation, in the long-term, is less of a threat to inshore reef coral communities than previously considered (Rogers 1990; McLaughlin *et al.* 2003; Kleypas & Eakin 2007). The net annual depositional rate was consistently lower than the mean seasonal sedimentation rate, although the difference between the two variables varied across the reef reflecting differences in the hydrodynamic regimes between reef habitats. These hydrodynamic differences resulted in spatially variable annual resuspension rates. For example, the proportion of sediments resuspended over longer time frames was 16% in the western basin at Middle Reef, but 84% on the leeward reef edge, and, as such, the difference between the net annual and seasonal mean sedimentation rate was greater on the leeward edge. At Paluma Shoals, no sediments had accumulated on the reef flat and windward edge over the year, despite sediment deposition on the seasonal tray. Although shorter-term seasonal sedimentation rates are a good indication of monthly and/or seasonal differences in sediment deposition, they do not necessarily give an accurate indication of the longer-term build up of sediments, particularly in highly dynamic hydrodynamic and sedimentary settings.

6.6.4 Sediment flux rate

Sediment trays measure intra-annual and annual sediment deposition and resuspension, and therefore can be used to assess the total mass of mobile sediments that are both deposited and resuspended at that site. Sediments that are both deposited and resuspended are part of a flux and hence, the total mass of mobile sediments is classified as the sediment flux rate. At Middle Reef, the sediment flux varied between 34 to 643 $g/m^2/day$, with highest rates occurring along the eastern windward reef edge. At Paluma Shoals, a single flux rate of 329 $g/m^2/day$ was measured on the protected leeward edge, but given that the annual resuspension rate was higher on the windward reef edge and turbidity fluctuated to >150 NTU, the flux rate is likely to be far greater here than on the leeward edge. These estimates of the total mass of sediments moving over each reef calculated with my method seem sensible in view of the 21, 000 tonnes per year flux rate through Western Channel (where Middle Reef is located) suggested by recent modelling (Lambrechts *et al.* 2010).

6.6.5 Implications for reef benthos

Spatially variable sediment flux rates examined with net annual sediment depositional rates provide a detailed assessment of the sedimentary conditions to which corals are exposed to on inshore turbid reefs. High flux rates occurred within reef habitats that were either exposed to high wave activity (e.g. the eastern windward reef edge) or were composed of fine sediments <90 μm which are more easily resuspended (e.g. the leeward edges on both reefs). Reef habitats with high flux rates (>100 $g/m^2/day$) and low net annual deposition (<25 $g/m^2/day$) had high coral cover (>50%), whereas reef habitats with high fluxes but high annual deposition of fine sediments (>25 $g/m^2/day$) had lower coral cover (<50%). Lowest coral cover (27%) was observed in regions of both low flux (<50 $g/m^2/day$) and high deposition (>50 $g/m^2/day$). Spatial variations in coral cover will ultimately influence coral carbonate productivity and reef growth.

It is widely reported that coral reefs exposed to high sedimentation (>100 $g/m^2/day$) and high turbidity (>20 NTU) have low coral cover and diversity (Rogers 1990), however, coral cover at Middle Reef and Paluma Shoals is >29% and contains a diverse coral community (>50 species; Veron 1995; Browne *et al.* 2010). The coral community is spatially distributed according to the corals ability to tolerate sedimentation and turbidity. For example, *Acropora* tend to dominate reef habitats where sedimentation rates (<50 $g/m^2/day$) and turbidity (<10 NTU) is low (e.g. windward edge at Middle Reef) whereas *Galaxea* typically dominate reef habitats exposed to high sedimentation (>50 $g/m^2/day$) and turbidity (>30 NTU) (e.g. leeward edge at Paluma Shoals; Table 6.2). However, for the most part, sedimentation rates derived using sediment trays were below levels previously considered detrimental for coral reef communities, suggesting that corals on Middle Reef and Paluma Shoals are not threatened by sedimentation despite high sediment loads. Furthermore, in protected reef habitats where sedimentation rates were close to and above the critical threshold of 100 $g/m^2/day$ as proposed by Rogers (1990), coral cover was still considered to be high (>30% e.g. leeward edge at Paluma Shoals), indicating that corals in these habitats have adapted to higher deposition. These data highlight the importance of recognising spatial variations in sedimentary regimes at the intra-reefal scale, and factoring in local adaptations to marginal reef growth conditions particularly on reefs that have been exposed to naturally high sediment loads since reef initiation.

6.7 Conclusions

Sediment trays provided quantitative data on a number of sedimentary parameters to provide a comprehensive assessment of sediment regimes on inshore turbid reefs. The technique is novel in that it quantifies both intra-annual and annual sedimentation rates, sediment resuspension and sediment flux rates. The application of sediment trays overcomes a number of disadvantages associated with sediment traps (e.g. over-estimation), and allows the user to distinguish between key sediment processes important for the interpretation of environmental consequences. The technique is robust, yet simple and involves minimal costs to build and maintain. Sediment trays were deployed in the field for a year and sediments were sampled every 4-6 weeks. A more field intensive survey design would provide additional information on shorter-term depositional and resuspension events, however, project costs and logistical considerations need to be taken into account. On-going experiments tailoring the sampling interval are currently underway, and a range of artificial sampling surfaces are being trialled. The survey design as implemented here provided a detailed analysis of sediment regimes across four seasons and between locations on two inshore turbid reefs. In doing so, it has established that prior assessments of sedimentation rates on the GBR are potentially an over-estimation and that resuspension rates are an important component of the sedimentary regime which has potentially permitted corals to survive and reefs to grow in high sedimentary conditions. Furthermore, data sets indicate that sedimentation and resuspension rates are highly variable spatially at the intra-reef scale. Data sets of this nature improve current understanding on sedimentary regimes and provide a more accurate estimation of sedimentary conditions to which corals are exposed. A potential application of this approach could be the development of site-specific coral thresholds to sediment stress. Lastly, sediment trays have a broader applicability for use in a range of habitats from deep sea to coastal marine and estuarine environments where sediments play an integral role, and can be adapted to suit user needs.

7. SPATIAL AND TEMPORAL VARIATIONS IN CORAL GROWTH ON AN INSHORE TURBID ZONE REEF SUBJECTED TO MULTIPLE DISTURBANCES

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7.1 Abstract

Coral growth rates (linear extension, density, calcification rates) of three fast-growing corals (*Acropora, Montipora, Turbinaria*) were studied *in situ* on Middle Reef, an inshore reef located on the central Great Barrier Reef (GBR), to assess the influence of changing environmental conditions on coral condition and reef growth. Middle Reef is subjected to both local (e.g. high sediment loads) and global (e.g. coral bleaching) disturbance events, usually associated with reduced coral growth. Results indicated, however, that *Acropora* growth rates (mean linear extension = 6.3 cm/year) were comparable to those measured at similar depths on offshore reefs on the GBR. *Montipora* linear extension (2.9 cm/year) was greater than estimates available from both clear-water and turbid reefs, and *Turbinaria's* dense skeleton (1.3 g/cm^3) may be more resilient to physical damage as ocean pH falls. Coral growth was found to vary between reef habitats due to spatial differences in water motion and sediment dynamics, and temporally with lower calcification rates during the summer months when SSTs (monthly average 29^{o}C) and rainfall (monthly total >500 mm) were high. In summary, corals on Middle Reef are robust and resilient to their marginal environmental conditions, but are susceptible to anthropogenic disturbances during the summer months.

7.2 Introduction

Turbid reefs are typically situated in shallow waters (<20 m) within close proximity to the coast (<20 km) where high sediment yields and wave-driven resuspension of fine sediments on the seafloor lead to large fluctuations in turbidity (0 to >100 mg/l; Lou & Ridd, 1996; Larcombe *et al.*, 2001; Browne *et al.*, in review-b). Suspended sediments reduce water transparency and limit light availability for phototrophic organisms (Loya, 1976; Anthony & Connolly, 2004), and if deposited, can smother and bury reef benthos (Hubbard, 1986; Fabricius & Wolanski, 2000; Philipp & Fabricius, 2003). Nutrient concentrations are also often elevated inshore, which stimulates macro-algal growth (De'ath & Fabricius, 2010), increases disease prevalence (Bruno *et al.*, 2003) and reduces coral reproduction (Koop *et al.*, 2001). These local stressors erode reef resilience, and therefore increase their vulnerability to global stressors that include ocean warming, predicted to increase the severity and intensity of coral bleaching events (Hoegh-Guldberg, 1999); ocean acidification, predicted to reduce calcification rates and reef growth (Kleypas *et al.*, 1999b, Hoegh-Guldberg *et al.*, 2007); and increased storm and cyclone activity (Webster *et al.*, 2005), predicted to reduce coral framework complexity and stability (Puotinen, 2004). While there is some detailed knowledge on how these individual stressors influence benthic communities, less is known on the long-term cumulative effects of multiple stressors on reef health, growth and development of inshore turbid reefs.

Fluctuations in reef health, in response to environmental change, can be monitored at the reef scale using benthic surveys or at the organism scale to assess physiological responses to environmental change (Bak, 1976; Cortes *et al.*, 1985). Benthic surveys are relatively simple to conduct, however, they are a discontinuous measurement of reef health. In contrast, techniques which assess physiological responses, such as variations in coral lipid content (Harriott, 1993) and coral growth rates (Highsmith, 1979; Cruz-Pinon *et al.*, 2003), provide fine-scale spatial and temporal resolution data to determine how environmental variables influence organism responses, and how this translates through to the reef scale. For example, variations in coral growth rates will have both short-term ecological consequences and, as coral carbonate is required for reef growth, will have long-term geological consequences. The rate at which corals grow and produce calcium carbonate for their skeleton is influenced by a number of key environmental controls: light (Bak, 1974), ‘sun-hours’ i.e. the number of hours of full sunlight (Bak, 1974), SST (Lough & Barnes, 2000), water motion (Scoffin *et al.*, 1992), water quality (Fabricius, 2005), plankton availability (Wellington, 1982), and carbonate saturation state (Marubini *et al.*, 2001). Corals less sensitive to fluctuations in these environmental parameters may continue to grow, outcompeting slow-growing corals for space on the reef, thereby influencing the equilibrium of species abundance (Jensen, 1987), carbonate production and reef growth.

It is commonly claimed that coral growth rates on inshore turbid reefs are lower than on offshore clear-water reefs, and have declined in the last ~50 years due to both local (sediments, nutrients) and global (SST, ocean acidification) pressures (Hendy *et al.*, 2003; Cooper *et al.*, 2008a; De'ath *et al.*, 2009; Veron *et al.*, 2009). The majority of coral growth rate studies have, however, been conducted on massive corals which are slow calcifiers (Lough & Barnes, 1997, 2000), and only a few studies have been conducted on the faster-growing species such as *Acropora* and/or sediment tolerant corals such as *Turbinaria* and *Montipora*. *Acropora* is both ecologically and geologically important to coral reefs because they are typically the primary calcium carbonate producer and reef framework builder (Veron, 1995), but low light conditions commonly experienced on turbid reefs has limited *in situ Acropora* growth assessments. *Turbinaria* and *Montipora* are plate corals that often dominate shallow water environments in the Indian Ocean and Asia-Pacific region (Veron, 2000), and are considered to be robust and resilient corals that have adapted to high turbidity conditions through heterotrophic feeding (Sofonia, 2006; Sofonia & Anthony, 2008, Anthony, 2006). However, few growth assessments of these corals have been conducted due to the associated difficulties in measuring and comparing growth rates of corals with variable plate morphologies (Heyward & Collins, 1985). Limited *in situ* assessments of these faster-growing corals will undermine knowledge on how these corals will respond to future environmental changes such as increased sediment yields and SSTs, and therefore, the consequences of these environmental changes for carbonate production and inshore turbid reef growth and development.

Here I examine coral growth rates for fast-growing and sediment tolerant species on Middle Reef, an inshore turbid reef on the central Great Barrier Reef (GBR). Inshore reefs represent approximately a third of the reefs on the GBR (Hopley *et al.*, 2007) and are widely reported as degraded since European settlement (McCulloch *et al.*, 2003; Fabricius *et al.*, 2005). Middle Reef is situated in Cleveland Bay ($19^0$11.70'S, 146^{0}48.70'E), where it is subjected to both global (e.g., coral bleaching, cyclones and associated flood events) and local (e.g., reduced water quality, dredging and physical damage) stressors. Previous reports suggest that reefs in Cleveland Bay either have been or are threatened by exposure to excessive sediment accumulation (Lambrechts *et al.*, 2010), high levels of nutrients (inorganic nitrates and phosphates; Scheltinga & Heydon, 2005) and trace metal contamination from port activities and urbanisation (Reichelt & Jones, 1994). The aim of this study was to investigate coral growth rates and carbonate production of fast-growing corals on an inshore turbid reef exposed to multiple global and local threats. Specifically I: 1) determined coral growth rates for the dominant fast-growing branching and plate corals, 2) assessed temporal variations in response to seasonal differences in environmental variables, and 3) investigated intra-reef spatial variations in coral growth. The implications of both temporal and spatial patterns of coral growth rates to reef growth and development are discussed together with the potential consequences of projected environmental changes that may lead to reduced coral growth and carbonate production.

7.3 Materials and Methods

7.3.1 Study site

Cleveland Bay has a 4 m thick layer of muddy sands and sandy muds over a muddy Pleistocene clay unit (Carter *et al.*, 1993), and accumulates sediments at an estimated rate of 60,400 tonnes/year (Lambrechts *et al.*, 2010). Wind-driven waves entering the bay resuspend sediments that are transported from the southern sections of the bay northwards through the Western Channel as turbid water (Lou & Ridd, 1997). Turbidity at Middle Reef can rise from <5 $mg.l^{-1}$ to around <100 $mg.l^{-1}$ after several days where significant wave heights exceeds >1 m (Larcombe *et al.*, 1995; Browne *et al.*, in review-b). It can also rise when flood plumes from Ross River reach Middle Reef, delivering freshwater as well as sediments; the last major flood event from the Ross River was in February 2009 when falling salinity levels (20 ppt near Middle Reef; Chin unpublished data) caused freshwater bleaching (pers. obs.). Flood plumes from the Burdekin River, the largest river draining into the central GBR, situated approximately 80 km further south (S), may also periodically influence Middle Reef

(McAllister *et al.*, 2000; Devlin & Brodie, 2005). Coral bleaching from elevated sea surface temperatures (SST) during the summer months (December to February) have also been observed at Middle Reef: in 1998 SST over 32°C were recorded, and resulted in a 10% decline in coral cover (Sweatman *et al.*, 2008). For a detailed description of Middle Reef refer to Chapter 3.

7.3.2 Biological parameters

7.3.2.1 Coral growth rates

Three corals (*Acropora formosa*, *Montipora aequituberculata*, *Turbinaria mesenterina)* widely distributed on Middle Reef and commonly found on other inshore turbid reefs (Osborne *et al.*, 1997; Sweatman *et al.*, 2007), were selected for coral growth studies. Coral growth rates were investigated using the Alizarin Red S staining technique (Oliver *et al.*, 1983; Gladfelter, 1984) from April 2009 to April 2010. Corals were stained *in situ* by placing a transparent plastic bag over the coral colony (<50 cm diameter) and injecting Alizarin Red S (10 ppm) into the bag. The plastic bags were sealed with a cable tie and removed after 4 hours. A total of 130 coral colonies were stained (80 *Acropora formosa*, 25 *Montipora aequituberculata*, 25 *Turbinaria mesenterina*) across three depth zones (>-1 m, -1 to -2 m, -2 to -3 m at LAT), within three reef geomorphological habitats (windward reef slope, leeward reef slope, inner basin reef slope), and across four sampling seasons (summer, autumn, winter, spring). Coral samples were collected 3 to 4 months (weather dependent) after staining to allow for both spatial and temporal assessments of coral growth. A branch of stained *Acropora* (<5 cm) or a cross-section through the plate corals (approximately 25 cm^2) were collected and bleached in 5% NaOCl solution in the laboratory for two hours to allow for the identification of new coral growth (the portion not stained pink). A total of 62 *Acropora,* 16 *Montipora* and 16 *Turbinaria* were successfully stained and used to determine coral growth rates.

7.3.2.2 Acropora

Linear extension (cm/year), bulk skeletal density (g/cm^3) and calcification rates (g/cm^2/year) were calculated each season for *Acropora* using established techniques. Linear extension was determined by measuring the length from the distal margin of the stained skeleton to the tip of the new growth (Gladfelter, 1984) and converted to an annual rate of growth by dividing the length (cm) by the number of days since coral staining, and multiplying by 365 days. Skeletal density (i.e., mass divided by the total enclosed volume) was determined using the water displacement technique (Oliver *et al.*, 1983; Bucher *et al.*, 1998), and the calcification rate was calculated by multiplying the linear extension by the density (Lough & Barnes, 2000). Linear extension and calcification rates were reported as annual rates to allow comparisons with previous coral growth assessments.

7.3.2.3 Montipora and *Turbinaria*

Previous measurements of plate coral growth have relied on either the buoyant weight technique (Spencer Davies, 1990) or measuring changes in colony dimension over time (Heyward *et al.*, 1985). However, the results from the buoyant weight technique are dependent on the initial sample size (Heyward *et al.*, 1985), and coral dimensions do not provide information on calcification rates, which are useful for comparative analysis with branching corals and critical for carbonate production studies. Therefore, I developed a new approach where the amount (g) of calcium carbonate was directly measured by removing and weighing the new growth. Prior to the removal of the new growth, a photograph was taken of the 2-dimensional surface area (cm^2) using CpCE software, which when multiplied by the weight gave a calcification rate, also reported as an annual rate. Density measurements were carried out using the water displacement technique, as for *Acropora*, and linear extension measurements were performed to provide comparative data, but were not used in statistical analysis because these measurements vary between corals due to both morphological and growth rate differences, and therefore, do not give an accurate estimation of coral growth.

7.3.3 Environmental parameters

7.3.3.1 Sedimentation rates

Sedimentation rates were measured at four locations (eastern windward slope, western windward slope, leeward slope, inner basin) using paired sediment trays as described in Chapter 6 (Fig. 6.2). Sediments were collected from the trays *in situ* using a hand-held air-lift suction device and transported to the laboratory where they were dried at 55^0C for 24 to 48 hours, weighed (to the nearest 0.001g) and analysed for particle size distribution.

7.3.3.2 Waves

Wave measurements were collected every 20 minutes during the survey period using a Nortek 2 MHz Acoustic Doppler Current Profiler (ADCP). ADCPs were deployed for up to two weeks, and two deployments were carried out to provide representative wave characteristics for the windward, inner and leeward reef slopes.

7.3.3.3 Turbidity and light

Turbidity measurements were recorded every 10 minutes using a nephelometer (refer to section 5.3.2) and light intensity profiles were measured at 0.5 m depth intervals from the sea surface to the sea bed (3 to 5 m) using a Li-Cor 192 sensor and a Li-250A light meter. The sensor is cosine corrected and measures photon flux density from 400-700 nm, and has a resolution of 0.01 µmol s^{-1} m^{-2}, appropriate for extremely turbid conditions. Measurements were conducted between 10 am to 12 pm, and cloud cover and wind speed were recorded. Light attenuations for 0.5 m depth bands were calculated as a percentage of the light available at the surface to allow for a comparison of relative values observed over time and space.

7.3.3.4 Meteorological data

Mean monthly wind ($km.hr^{-1}$) and water temperature (^oC at 8 m) data were obtained from an Australian Institute of Marine Science (AIMS) weather station, located on the S5 shipping Platypus Channel marker situated approximately 7 km NE of Middle Reef (Fig. 1.1). The AIMS weather station, situated in Bowling Green Bay, approximately 50 km east (E) of Middle Reef, provided mean monthly surface irradiance ($uE/m^2/s$) data, and the Bureau of Meteorology weather station at Nelly Bay, Magnetic Island (4 km NE of Middle Reef; Fig. 1.1) provided mean monthly rainfall (mm).

7.3.4 Statistical analysis

One-way ANOVAs with a *post hoc* test (Bonferroni method) were conducted in SPSS (version 17) to determine if coral growth variables (linear extension, skeletal density, calcification rate) varied significantly ($p<0.05$) with seasonal fluctuations (winter, spring, summer, autumn) in SSTs, sun light hours, rainfall, and sediments, and spatially with depth and habitat (windward, inner and leeward reef slopes). Pearson's correlation coefficients were also used to determine if coral growth rates were significantly related to light attenuation, independent of depth.

7.4 Results

The mean linear extension rate across all sampling seasons was 6.3 $\pm$ 0.4 cm/year for *Acropora* (range = 1.5 to 14.2 cm/year), 2.9 $\pm$ 0.3 cm/year for *Montipora* (range =0.5 to 5.8 cm/year), and 1.1 $\pm$ 0.2 cm/year for *Turbinaria* (range = 0.7 to 1.5 cm/year). *Acropora* had a mean skeletal density of 1.03 g/cm^3, while *Montipora* had the least dense skeleton ranging from 0.7 g/cm^3 to 1.3 g/cm^3 (mean = 0.9 $\pm$ 0.04 g/cm^3), and *Turbinaria* had the most dense skeleton ranging from 0.95 g/cm^3 to 1.7 g/cm^3 (mean = 1.3 $\pm$ 0.05 g/cm^3). Coral growth rates varied significantly between sampling seasons and/or spatially with depth and between reef habitats (Table 7.1).

Table 7.1: Summary of statistical analysis of coral growth rates. Significant results are in bold.

ONE - WAY ANOVA			*Acropora*				*Turbinaria*				*Montipora*			
Growth Measure	**Variable**		**n**	**P value**	**Mean**	**SE**	**n**	**P value**	**Mean**	**SE**	**n**	**P value**	**Mean**	**SE**
Linear extension	Depth	>-1 m	11		4.9	0.6								
		-1 to -2 m	16	**0.022**	8.6	0.6								
		<-2 m	8		6.1	0.9								
Density	Depth	>-1 m	11		1	0.09	2		1.3	0.11	9		0.98	0.06
		-1 to -2 m	16	0.110	1	0.03	7	0.775	1.3	0.07	4	**0.025**	0.97	0.06
		<-2 m	8		0.9	0.1	1		1.5	0.1	3		0.74	0.02
Calcification	Depth	>-1 m	11		4.8	0.6	2		4.9	1.7	9		1.49	
		-1 to -2 m	16	**0**	8.6	0.6	7	0.499	2.9	1	4	0.285	1.27	
		<-2 m	8		5	0.6	1		1.3	0.8	3		1.93	
Linear extension	Habitat	Windward	15		8.9	0.6								
		Inner	7	**0**	3.9	0.3								
		Leeward	13		5.3	0.6								
Density	Habitat	Windward	15		0.9	0	2		1.1	0	7		0.92	0.06
		Inner	7	0.62	0.9	0.1	2	0.374	1.4	0.1	4	**0.025**	0.79	0.05
		Leeward	13		1	0.1	6		1.4	0.1	5		1.07	0.04
Calcification	Habitat	Windward	15		8.4	0.6	2		6.8	0.1	7		1.75	
		Inner	7	**0**	3.6	0.3	2	**0.018**	0.8	0.1	4	**0.043**	1.42	
		Leeward	13		5.1	0.6	6		2.7	0.8	5		1.27	
Linear extension	Season	Winter	15		6.45	0.66								
		Spring	6	**0.044**	4.83	0.69								
		Summer	6		3.68	1.1								
		Autumn	35		6.9	0.5								

Table 7.1 continued

Growth Measure	Variable		n	P value	Mean	SE	n	P value	Mean	SE	n	P value	Mean	SE
Density	Season	Winter	15		1.15	0.05	5		1.27	0.08	5		1.02	0.07
		Spring	6	**0.022**	1.16	0.16	3	0.427	1.22	0.21	1	0.470	0.83	0.05
		Summer	6		0.85	0.05	4		1.43	0.12	2		0.97	0.15
		Autumn	35		0.99	0.04	4		1.19	0.09	8		0.89	0.06
Calcification	Season	Winter	15		7.45	0.97	5		5.09	1.22	5		1.41	
		Spring	6	**0.034**	5.38	0.68	3	**0.032**	3.4	0.36	1	0.958	1.72	
		Summer	6		3.2	1	4		1.71	0.3	2		1.47	
		Autumn	35		6.6	0.48	4		5.91	0.62	8		1.57	
Pearson's correlation coefficient					**R^2**				**R^2**				**R^2**	
Linear extension				0.416										
Density			35	0.670			10	0.223			16	0.457		
Calcification rate			35	0.252			10	**0.021**	-0.71		16	0.385		

7.4.1 Temporal variations

Temporal variations in coral growth rates were assessed between the four seasons: summer (December to February), autumn (March to May), winter (June to August) and spring (September to November). Summer was characterised by high SST (28.6^{o}C), high rainfall (mean 507 mm/month), high surface irradiance (434 PAR) and strong winds (>20 km.hr^{-1} for 14% of the summer), where as winter was characterised by low SST (22.2^{o}C), low rainfall (mean 0.33 mm/month), reduced surface irradiance (321 PAR) and lighter winds (>20 km.hr^{-1} for 6% of the summer; Table 7.2). However, sedimentation rates were highest during the autumn months (72 g/m^2/day) and comparatively low in both spring, summer and winter (<43 g/m^2/day). *Acropora* linear extension, density and calcification rates varied significantly ($p<0.044$) between seasons with low coral growth (calcification rate = 3.2 g/cm^2/year), occurring during the wet, windy summer months (Fig. 7.1; Table 7.1). During autumn, linear extension rates (6.9 $\pm$ 0.5 cm/year), and calcification rates increased (6.6 g/cm^2/year), and in winter skeletal densities increased (1.15 g/cm^3), resulting in a further increase in calcification rates (7.5 g/cm^2/year). During spring, densities remained high but linear extension rates were reduced (4.83 $\pm$ 0.69 cm/year) and, as such, calcification rates fell (5.4 $\pm$ 0.68 g/cm^2/day). *Turbinaria* and *Montipora* skeletal densities did not vary significantly between seasons ($p>0.05$), but *Turbinaria* calcification rates were significantly different across the seasons ($p=0.032$; Fig. 7.1), with highest coral growth rates (>5 g/cm^2/day) occurring during the autumn (despite low skeletal densities) and winter months. *Montipora* calcification rates did not vary significantly over the year.

Table 7.2: Seasonal variations in environmental conditions.

Season	Environmental variables				
	Mean monthly SST (^{o}C)	**Mean monthly rainfall (mm)**	**PAR (uE/m²/s)**	**Mean monthly wind speed (km.hr^{-1})**	**Sedimentation rate (g/m^2/day)**
Winter	22.20	0.33	320.99	16.22	42.40
Spring	25.70	31	437.98	21.04	42.57
Summer	28.59	507	433.73	22.12	36.00
Autumn	25.67	92	332.48	21.5	72.57

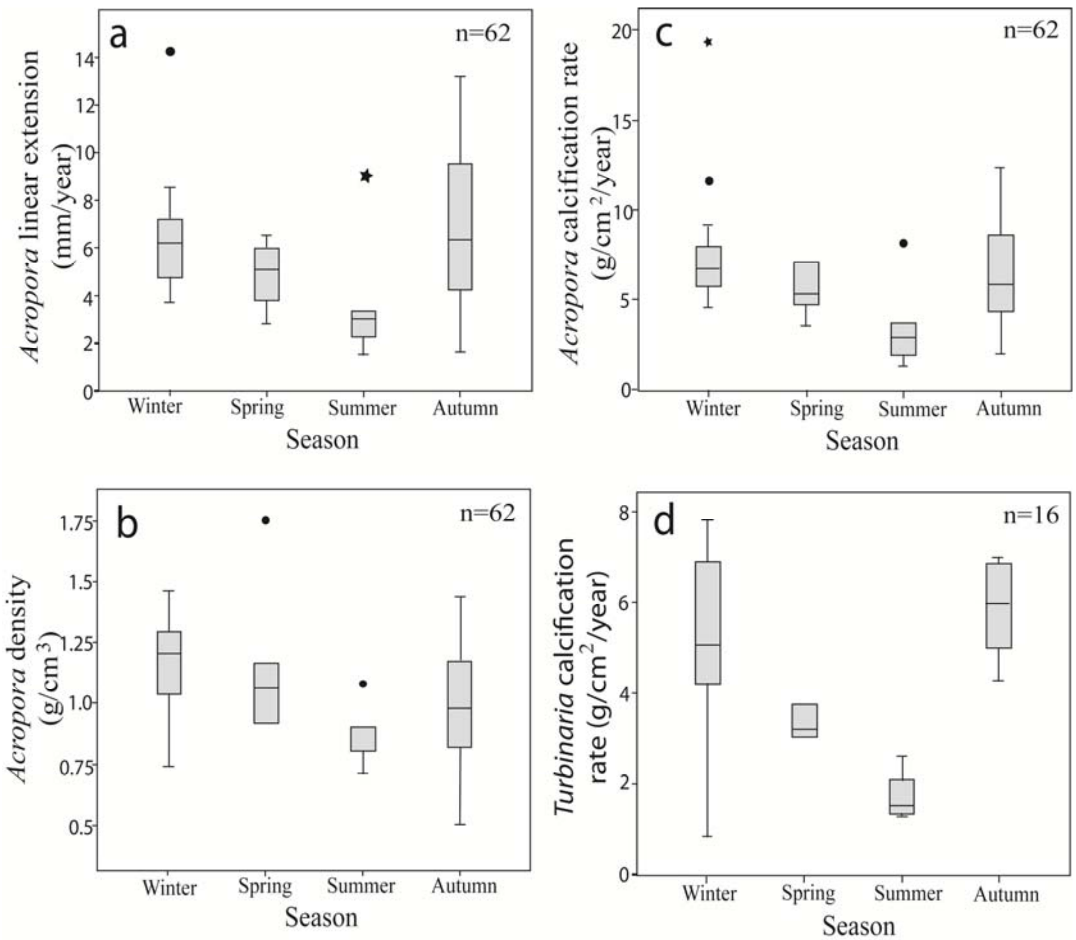

Figure 7.1: Temporal variations in (a) *Acropora* linear extension, (b) *Acropora* density, (c) *Acropora* calcification rates, and (d) *Turbinaria* calcification rates. Outliers denoted by a filled circle and extreme outliers denoted by a star. Note different scale used for Turbinaria calcification rate.

7.4.2 Spatial variations

Spatial variations in coral growth were assessed using: *Acropora* samples stained in autumn as growth rates during this period were close to average for the year and included approximately half of the corals successfully stained (35 samples); *Turbinaria* samples stained in autumn and winter when coral growth rates were not significantly different (10 samples); and all *Montipora* samples as there was no significant difference in coral growth between seasons (16 samples).

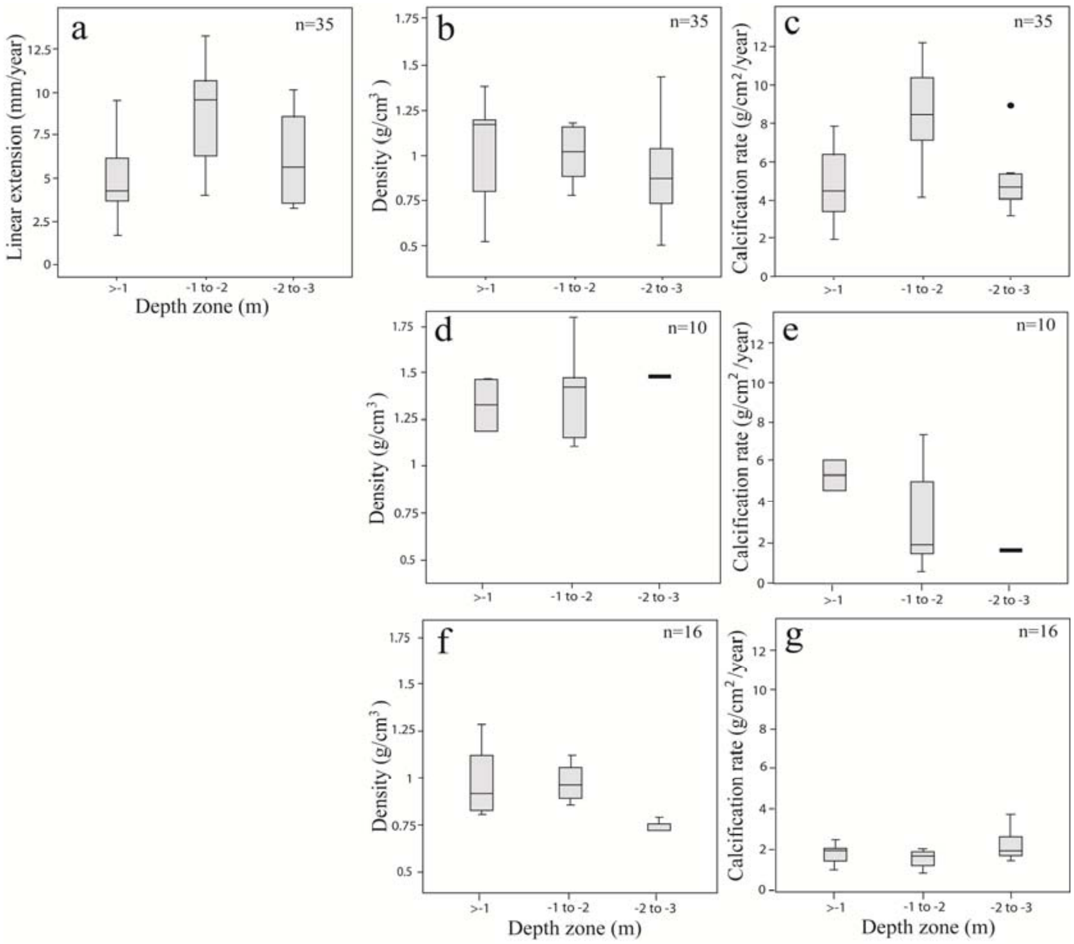

Figure 7.2: Coral growth rates (linear extension, density, calcification rates) for *Acropora* (a,b,c), *Turbinaria* (d,e) and *Montipora* (f,g) within three depth zones. Outliers denoted by a filled circle.

Depth

Acropora linear extension rates and calcification rates varied significantly with depth ($p<0.02$), with highest linear extension (8.6 cm/year) and calcification rates (8.6 g/cm^2/year) occurring between -1 to -2 m below LAT (Fig. 7.2). However, *Turbinaria* and *Montipora* calcification rates were not significantly different between depth zones. Density did not vary significantly with depth for *Acropora* and *Turbinaria*, but were significantly ($p=0.025$) different with depth for *Montipora,* whose density decreased from 0.98 $\pm$ 0.06 g/cm^3 at >-1 m to 0.74 $\pm$ 0.02 g/cm^3 at <-3 m.

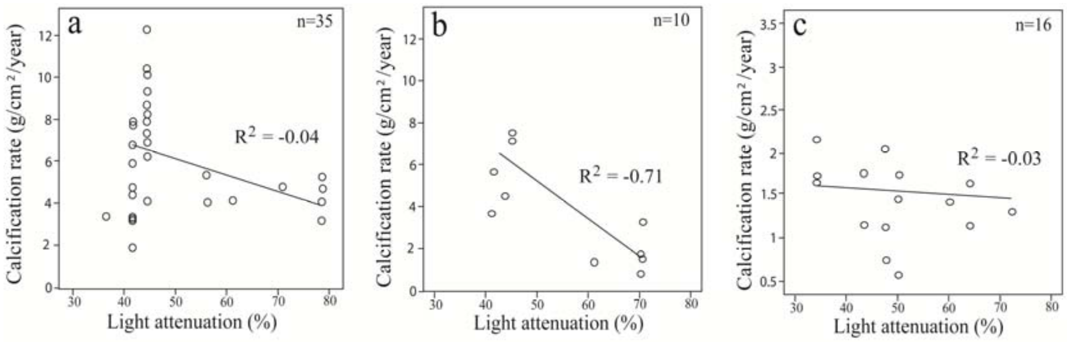

Figure 7.3: Calcification rates for (a) *Acropora,* (b) *Turbinaria* and (c) *Montipora,* at different light attenuations (%). Calcification rates are consistently low when light attenuation is over 50% for all three corals and are consistently high when light attenuation is <50% for *Turbinaria*. The range of values for *Acropora* and *Montipora* at low light attenuation suggests other environmental factors are influencing coral growth. Note different calcification scale used for *Montipora*.

Light availability

Light attenuation with depth varied between habitats, with the greatest fall in light availability occurring on the leeward edge (Table 7.3). Pearson's correlation coefficient tests indicated that only *Turbinaria* calcification rates were significantly negatively correlated with light attenuation (p=0.021, R^2 = -0.712). However, *Acropora* and *Montipora* calcification rates were consistently low in reef regions of low light availability (>50%; Fig. 7.3).

Reef geomorphology

There were significant differences in coral growth rates for all three coral species between the windward edge, inner slopes and the leeward edge (Fig. 7.4). *Acropora* linear extension and calcification rates were significantly greater (p<0.005) along the windward edge where wave energy was higher (mean wave height = 0.21 m) and light attenuation was lowest (<56% at -3 m), and lowest within the inner reef basins where sediment deposition was high (74 $g/m^2/day$; Table 7.3) and turbidity fluctuations were large (<100 $mg.l^{-1}$). *Turbinaria* density did not vary significantly between habitats, but calcification rates were also significantly greater (p< 0.05) along the windward edge, as were *Montipora* calcification rates (p<0.05, n = 12, 4 outliers were removed).

Table 7.3: Spatial variations in light attenuation with depth and habitat, and spatial variations in wave height and sedimentary regimes between the three reef habitats at Middle Reef.

Habitat	Light attenuation (%)			Wave height (m)			Sedimentary regime		
	>-1 m	.-1 to -2 m	<-3 m	Mean	Min	Max	Dominant sediment type	Mean net deposition ($g/m^2/day$)	Turbidity range at 3 m LAT ($mg.L^{-1}$)
Windward	25.5	44.5	56.1	0.21	0.06	1.74	Gravelly sands	42.0	2 to 50
Inner	36.6	49.2	61.3	0.17	0.05	0.64	Muddy sands to sandy muds	74.0	10 to 100
Leeward	41.6	70.9	78.6	0.16	0.06	0.57	Muddy sands	30.0	5 to 60

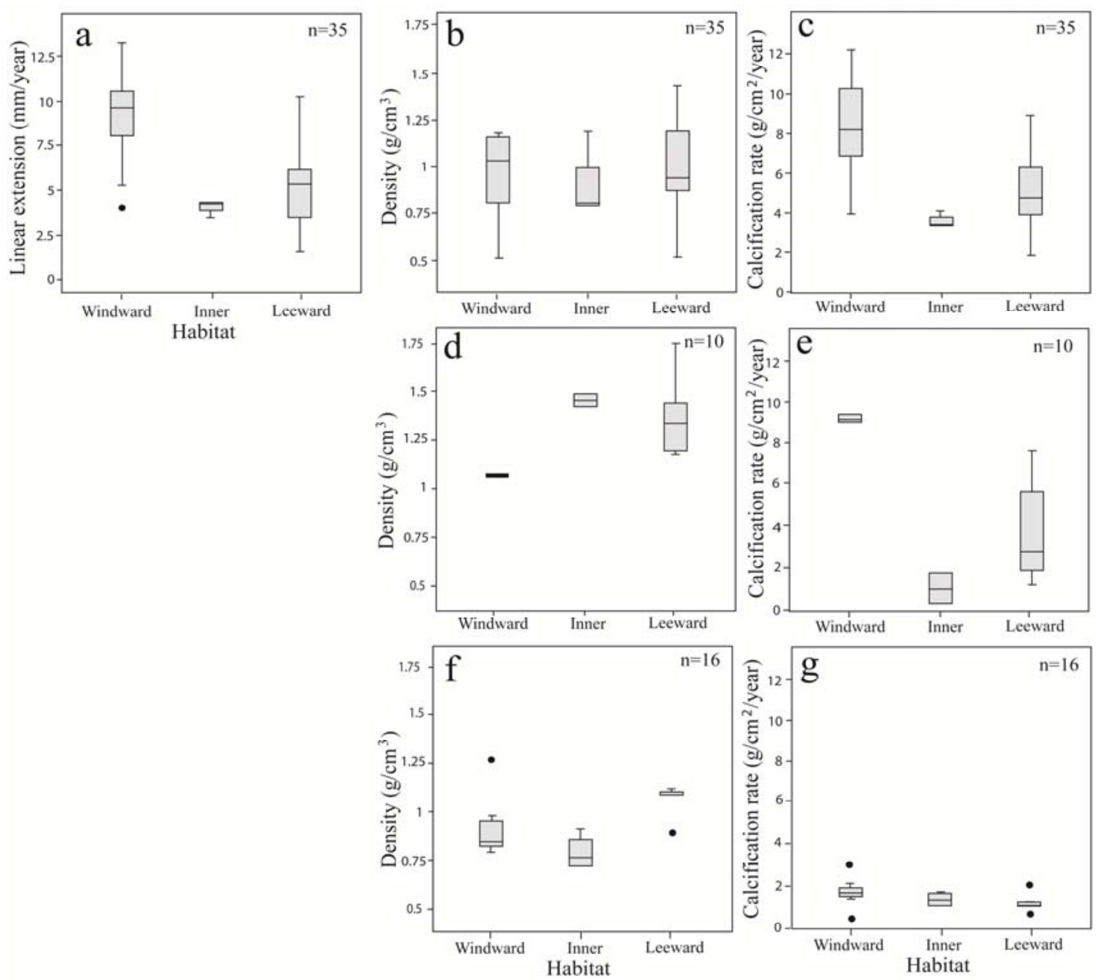

Figure 7.4: Coral growth rates (linear extension, density, calcification rates) for *Acropora* (a,b,c), *Turbinaria* (d,c) and *Montipora* (f,g) within the three reef habitats. Outliers represented by a filled circle.

However, *Montipora* density was significantly greater ($p<0.02$) on the leeward edge which had the lowest sedimentation rates (30 $g/m^2/day$), but the highest light attenuation due to resuspension of fine muddy sands (Table 7.3).

7.5 Discussion

High coral growth and calcification rates at Middle Reef contradict claims that corals growing in turbid waters have slower growth rates than corals on clear-water reefs due to the associated negative effects of high sediment loads and reduced water quality (Dodge *et al.*, 1974; Tomascik & Sander, 1985; Risk & Sammarco, 1991). *Acropora* mean linear extension rates on Middle Reef were comparable to rates measured on mid-shelf (e.g. 7.13 cm/year at Lizard Island; Oliver, 1985) and offshore reefs (e.g. 8 cm/year at Davies Reef; Oliver *et al.*, 1983) at similar depths (<5 m) and SSTs (~26 ^oC; Table 7.4). *Acropora* skeletal density and calcification rates were also similar to *Acropora* densities on mid and offshore clear-water reefs on the GBR (Oliver *et al.*, 1983; Bucher *et al.*, 1998), and *Acropora* calcification rates in the Caribbean where waters are typically less turbid (Gladfelter, 1984). Studies that report higher growth rates (e.g. <33.3 cm/year in Sulawesi (Crabbe & Smith, 2005)) have been conducted either at greater depths (>5 m) or in regions characterised by higher SSTs (~28 ^oC), environmental conditions that lead to increased coral growth. Furthermore, data on *A.formosa* linear extension rates (~7 cm/year; Oliver, 1984) on a fringing reef of Magnetic Island from the 1980's, suggest that *Acropora* corals on Middle Reef have adapted to their marginal growth conditions as evidenced by temporally stable growth rates despite increased coastal development in Cleveland Bay over the last 30 years (Townsville City Council).

Montipora and *Turbinaria* often dominate shallow reef environments and are, therefore, important sources of carbonate for inshore turbid reef growth and development. However, no prior assessments of their *in situ* calcification rates ($g/m^2/year$) have been published. The technique developed in this study shows that *Montipora* (1.52 $g/cm^2/year$) produces carbonate at similar rates to massive corals such as *Porites* (~1.6

Table 7.4: A summary of coral growth rates for *Acropora, Montipora* and *Turbinaria* for reefs in Australia, the Caribbean and in Asia.

Species	Location	Site description	Depth (m)	Mean water temp. (^{0}C)	Linear growth (cm/year)	Density (g/cm^3)	Calcification rate (g/cm^2/ year)	Reference
A.formosa	Middle Reef, GBR	Linear patch reef	0 to 3	26	6.26	1.03	1 to 19.2	This study
A.formosa	Magnetic Island, GBR	Shallow fringing reef slope in turbid waters	3	26	~7			Oliver, 1984
A.formosa	Lizard island, GBR	Fringing reef		26	7.13			Oliver, 1985
A.formosa	One Tree Island, GBR	Sheltered leeward end of a lagoon	5 to 10			1.09		Bucher *et al*., 1998
A.formosa	Davies Reef, GBR	Patch reef	5	27	8	0.5 to 1.5		Oliver *et al*., 1983
			10		12.4			
A.formosa	Houtman Abrolhos, Western Australia	Patch reef	2 to 3	21	3.7 to 7.6			Crossland, 1981
A.formosa	Houtman Abrolhos, Western Australia	Protected lagoonal site	7 to 11	21	7.6			Harriot, 1998
		Reef slope exposed to oceanic swell	7 to 11	21	5.3			
A.formosa	Dampier Archipelago	Fringing reef flat in clear-water and low sediment deposition	4	26	13.7			Simpson, 1988
A.formosa	Thailand	Fringing reef slope	3	28.2	~8			Charuchinda & Hylleberg, 1984
A.formosa	Samoa			28	18.5			Mayor, 1924
A.formosa	Sri Lanka	Open shallow reef lagoon	0.5 to 1.5	>27.5	11.2			Jinendradasa & Ekaratne, 2000
		Semi-enclosed bay	0.5 to 1.5	>27.5	12.1			
A.cervicornis	Discovery Bay, Jamaica	Rio Bueno	5 to 8.5		11			Crabbe, 2009
		Dairy Bull	5 to 8.5		14.6			
		Pear Tree Bottom	5 to 8.5		9.2			
A.cervicornis	Buck Island, US Virgin Islands	Forereef	8		7 to 11		12 to 20	Gladfelter, 1984
A.cervicornis	San Cristobal, Puerto Rico	Patch reef	4		7.1			Rogers, 1979
A.longicyathus	One Tree Island, GBR	Shallow reef lagoon	~1	18.2 to 30.4	4.1	1.25		Koop *et al*., 2001
A.valeniennesi	Sulawesi, Indonesia	Patch reef with high turbidity and human influences	10	27.2 - 28.9	7 to 11			Crabbe & Smith, 2005
		Fringing reef with intermediate water clarity & human influences	10		13.5 to 28.2			
		Patch reef with low turbidity and human influence	10		14.2 to 33.3			
A.palmata	Discovery Bay	Rio Bueno	5 to 8.5		5.5			Crabbe, 2010
		Dairy Bull	5 to 8.5		8			
		Pear Tree Bottom	5 to 8.5		6.5			
A.palmata	Curacao, Caribbean		2 to 3	25 to 29.5	7 to 9			Bak *et al*., 2009
M.aequiterculata	Middle Reef, GBR	Linear patch reef	0 to 3	26	2.88	0.94	1.52	This study
M.verrucosa	Kaneohe Bay, Hawaii	Laboratory experiment	3				27.6 + 15.1 mg/day	Spencer Davies, 1991
M.verrucosa	Kaneohe Bay, Hawaii	Patch reef, reef slope	1.75	27.5	1.3			Grottoli, 1999
			5		1.3			
			8.3		2.2			
M.digitata	Magnetic Island, GBR	Fringing reef flat	0.4 above LAT	25	<3			Heyward & Collins, 1985
Montipora sp.	Sulawesi, Indonesia	Patch reef with high turbidity and human influences	10		0.2			Crabbe & Smith, 2005
		Fringing reef with intermediate water clarity & human influences	10		0.9			
		Patch reef with low turbidity and human influence	10		1			
T.mesenterina	Middle Reef, GBR	Linear patch reef	0 to 3	26	1.05	1.3	3.75	This study
T.mesenterina	Magnetic Island, GBR	Lab based experiment	2 to 4	23.5	<3.9 % increase in monthly growth rate			Sofonia & Anthony, 2008

g/cm^2/year; Lough and Barnes 2000; Cooper *et al.*, 2008a), but that *Turbinaria* (3.75 g/cm^2/year) calcifies more rapidly. Data on linear extension rates is available for a few *Montipora* spp., and comparisons with Middle Reef data suggest that *M. aequibertalata* linear growth on Middle Reef is high despite differences in SST and depth ranges between studies (Table 7.4). High *M. digitata* linear extension rates (2.4 cm/year) have also been recorded on Magnetic Island (Heyward *et al.*, 1985) and may partly explain the high abundance of both species on reefs in Cleveland Bay. *Turbinaria* linear extension rates were comparatively low (1.05 cm/year), but densities were high compared to both *Montipora* and *Acropora,* which may provide *Turbinaria* with increased resilience to high wave energy within the shallow inshore regions. This attribute may become important if ocean pH continues to fall weakening coral skeletons and increasing coral susceptibility to physical damage.

7.5.1 Temporal variations

Low calcification rates for *Acropora* and *Turbinaria* in summer suggest that these corals are less resilient to anthropogenic influences in summer but high calcification rates in autumn indicate rapid recovery potential. Seasonal differences in *Acropora* growth rates have been observed in some but not all field studies (Crossland, 1984; Yap & Gomez, 1984), and where seasonal differences have occurred, growth is typically greater in summer due to warm seas (Crossland, 1981; Simpson 1988) and increased number of sunlight hours (Wellington & Glynn, 1983; Meyer & Scultz, 1985). Where seasonal differences have not been observed, SSTs have remained within the optimum temperature range and all other sea conditions have not been limiting (Gladfelter, 1984; Jinendradasa & Ekaratne, 2000). In this study, however, the combined effect of high SSTs, high rainfall (>400 mm/month) and reduced salinity, strong winds (>20 km.hr^{-1}) and increased turbidity in summer has reduced coral tolerances to conditions not previously considered stressful (e.g., salinities <30 ppt can reduce coral tolerance to high SST; Coles & Jokiel, 1978) and, as such, reduced coral growth. A similar response in *A. formosa* was observed in Thailand with reduced linear extension rates (~7 cm/year) occurring during the wet, warm summer months when sediment loads were also elevated (Charuchinda & Hylleberg, 1984). However, coral calcification rates increased in autumn and were highest in winter, suggesting that during the cooler months corals are potentially more robust and, therefore, more resilient to anthropogenic influences. Acknowledging seasonal differences in coral condition is critical for coastal management initiatives that aim to reduce stressors for inshore turbid reefs.

7.5.2 Vulnerability to changing environmental conditions

Coral growth rates from slow-growing massive corals suggest that calcification rates on inshore turbid reefs of the GBR are falling in response to increased sediment delivery rates and deteriorating water quality (see review by Fabricius, 2005). However, growth rates at Middle Reef are comparable to clear-water reefs, which may be explained, in part, due to relatively rapid flushing rates of the GBR lagoon (within weeks) that prevent the build up of nutrients in inshore regions (Brinkman *et al.*, 2002), but is most likely due to coral adaptations to marginal conditions inshore, particularly to sediment loads which have been elevated since the early Holocene (Larcombe & Woolfe, 1999b). Spatial variations with depth and between the windward to leeward edge do, however, suggest that corals are responding to fluctuations in light, wave exposure and sedimentation. Calcification rates were consistently low for all three corals when light attenuation was >50%, indicating a degree of dependency on light. Calcification rates were also consistently higher along the windward edge where waters were less turbid, and lower in the inner reef habitats were sedimentation rates were high (mean 72 $g/m^2/day$) and turbidity fluctuated to <100 $mg.l^{-1}$. These results suggest that despite high sediment loads, the associated negative effects of sediments to inshore turbid reefs is limited to small areas on the reef, typically within protected reef habitats where fine sediments are deposited.

The influence of global climate change on coral growth and carbonate production is unclear due to the synergistic effects of ocean acidification and rising SSTs. Ocean pH is predicted to decrease by 0.2 to 0.3 over the next 100 years (IPCC, 2007), which will weaken coral skeletons, reduce calcification rates (Anthony *et al.*, 2011) and increase corals susceptibility to physical damage from wind and wave activity. At present there is no evidence to suggest that the direct effects of ocean acidification will occur to a greater degree on inshore reefs than off shore reefs, particularly if current skeletal densities are comparable to offshore clear-water reefs. Nevertheless, corals in shallow inshore waters (<15 m) are exposed to higher wave activity than corals in deeper offshore waters (>15 m), and therefore are at higher risk of physical damage and reef framework removal. It is also predicted that the average SST will increase by >1^{o}C by 2099 under low emission scenarios (IPCC, 2007). Some studies suggest that coral calcification rates have increased due to rising SST (Lough *et al.*, 2000; Bessat & Buigues, 2001), while others suggest that rates may potentially decrease due to increasing temperature stress and ocean acidification (De'ath *et al.*, 2009). In contrast, a model by McNeil *et al.* (2004) predicts that calcification rates will increase with future ocean warming and exceed pre-industrial rates by 35% despite falling ocean pH. This study illustrates that for inshore turbid reefs on the central GBR, increasing SSTs are associated with reduced coral growth for faster-growing corals due to the additional stress effects such as high rainfall and reduced salinity, demonstrating the need to take into account local stressors in predicting the influence of global climate change on coral reefs.

Corals that can either grow rapidly (*Acropo*ra) or adapt well to their environmental setting (*Turbinaria, Montipora*) will become important species on reefs exposed to global and local stressors. In this study, I found that *Acropora*, although a fast-growing coral on inshore reefs and a primary carbonate producer, was more strongly influenced by seasonal changes than *Turbinaria* and *Montipora*, which calcify less rapidly but are also known to be more resilient to increased sediment loads. Acknowledging these differences may enable us to predict how coral communities may adapt over time in response to changing environmental conditions and assess reef vulnerability to degradation. For example, if a reef subjected to increased sediment loads results in a switch from fast-growing corals, such as *Acropora*, to more sediment tolerant coral species, such as *Turbinaria* with higher skeletal densities, there is potential for a higher tolerance to ocean acidification and storm damage despite lower carbonate production rates.

7.5.3 Reef growth

This study demonstrates the importance of *in situ* field studies in the assessment of coral growth responses to small-scale (<1 km) changes in multiple environmental drivers, and how these responses may influence reef growth. In laboratory based experiments, sediments loads greater than observed on Middle Reef were found to have no significant influence on *Turbinaria* and *Montipora* skeletal growth (Sofonia, 2006; Sofonia *et al.*, 2008), which would suggest that there would be little spatial variation in growth across Middle Reef. Specifically, these studies found that *T. mesenterina* was able to tolerate extremely high sedimentation rates (>1,100 $g/m^2/day$) in both low and high water flow (~20 $cm.s^{-1}$), and at low light regimes (<300 micro Einstein's m^{-2} s^{-1}) with limited influence on its growth. The same study showed that *M. digitata* could tolerate extremely high sediment loads up to 2,500 $g/m^2/day$ within a wide range of temperatures and light levels for up to 15 days. However, in the field, additional environmental variables, controlled for in the laboratory (e.g. temperature, salinity), may stress corals and reduce tolerance levels to sedimentation, resulting in spatially variable coral growth rates. Spatially variable growth rates will result in an uneven distribution of carbonate production and reef accretion rates will vary over the reef. The resulting changes in reef morphology will alter water flow and sediment dynamics which will in turn influence coral growth rates to produce a positive feedback mechanism that effects future reef growth.

The implications of reduced coral growth and carbonate production due to environmental change will have different consequences for reefs at or close to sea level compared to those with available accommodation space for reef growth. Reduced coral growth rates indicate lower coral condition and may lead to a fall in coral cover and diversity, key elements of reef resilience (Nystrom *et al.*, 2008). But for reefs, like Middle Reef, that are now close to sea level, a reduction in coral growth rates may prolong the active reef growth phase until they reach sea level (Smithers *et al.*, 2006; Perry & Smithers, 2011). Once they reach sea level, reef growth either switches from vertical to lateral growth, or the reef becomes a senile reef characterised by slow or no growth and reef sediment infilling, eventually leading to reef degradation. Therefore, implications of reduced coral growth rates for the long-term reef growth and development of rapidly accreting turbid reefs in shallow (<5 m) waters may not necessarily be detrimental to their survival on geological time-scales.

7.6 Conclusions

In conclusion, data on coral growth and carbonate production suggest that despite local anthropogenic pressures and global climate change, Middle Reef has a robust and resilient coral community. *Acropora* growth rates were comparable with coral growth rates observed at similar depths and SST on mid to offshore reefs on the GBR, and in the Caribbean. The lack of field studies of *Montipora* and, in particular, *Turbinaria* limit the extent of comparative analysis, as does the variations in techniques used to assess coral growth. However, *Montipora* and *Turbinaria* are abundant on inshore turbid reefs due to their adaptive capacities and are therefore, an important source of carbonate for reef growth and development. In this study, *Montipora* linear extension was greater than current estimates available, and *Turbinaria*, although characterised by slow linear extension, had a dense skeleton and hence may be more resilient to physical damage as ocean pH falls. Spatial variation were driven by water motion and sediment dynamics, and temporal variations, observed in *Acropora* and *Turbinaria*, indicate that although corals maybe more susceptible during the warmer months due to multiple stressors, they were able to rapidly recover during the cooler months. This study highlights the usefulness of measuring coral growth *in situ* in response to multiple stressors, to assess implications of environmental change on carbonate production and reef growth.

8. CARBONATE AND TERRIGENOUS SEDIMENT BUDGETS FOR INSHORE TURBID REEFS ON THE GREAT BARRIER REEF

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8.1 Abstract

Inshore turbid zone reefs on the Great Barrier Reef (GBR) occur within 20 km of the mainland coast under marine environmental conditions (with respect to sedimentation rates, turbidity and water quality) that are generally considered marginal for reef growth. However, data from various benthic habitat assessments report high (>30%) coral cover in these environments and reef core records show them to be characterised by rapid rates of vertical accretion (>2 mm/year), a long-term trend indicative of high carbonate productivity. However, the lack of quantitative data on terrigenous sediment input and flux rates, and on carbonate production rates has inhibited understanding of both ecological timescale rates of carbonate production and the aggregated long-term net impacts of sediments on reef growth. To address this knowledge gap a carbonate budget and terrigenous sediment model, that quantified allochthonous sediment inputs onto, within and off reef, was developed at two inshore reefs: Middle Reef and Paluma Shoals. Both are located within the central region of the GBR and are subjected to high terrigenous sediment load (>11,000 tonnes/year) and fluctuating turbidity (5 to >100 mg/L) regimes. Based on sediment dynamic modelling, over 81% of sediments delivered were transported off reef, with net sediment accumulation limited to sheltered reef habitats. Net carbonate production was high (>6.9 kg/m^2/year) due to high coral cover (>30%), high coral calcification rates (*Acropora* average 6.3 mm/year), and low bioerosion rates (0.3 to 5 kg/m^2/year), but varied spatially with highest net carbonate production (>10 kg/m^2/year) within deep (>-2 m at LAT) windward reef zones. High carbonate framework production has enabled Middle Reef and Paluma Shoals to vertically accrete rapidly: Middle Reef establishing at depths of ~ 4 m, Paluma Shoals at ~3 m depth and both reaching sea level in <1,200 years. This has occurred despite high

terrigenous sediment inputs and fluctuating turbidity. Carbonate and terrigenous sediment inputs were used to develop a reef growth model with time and depth, and illustrates how rates and modes of reef growth vary temporally as a reef approaches sea level. Both Middle Reef and Paluma Shoals are still actively accreting, although parts of the reef at sea level may, in the future, 'turn-off' despite high coral cover and carbonate productivity.

8.2 Introduction

Turbid zone reefs on the central Great Barrier Reef (GBR) are situated inshore (within <20 km of the mainland coast) in shallow water (<20 m) where high sediment yields and wave-driven resuspension of fine sediments from the seafloor lead to large fluctuations in turbidity (0 to >100 mg/l). Suspended sediments reduce light availability for photosynthesis and energy production (Rogers, 1990; Wolanski & De'ath, 2005), and deposited sediments can increase coral mortality by smothering and burial (Loya, 1976), reduce larval settlement, and increase the prevalence of tissue infections (Bruno *et al.*, 2003; Nugues & Callum, 2003; Fabricius, 2005). Sediments are delivered to inshore regions through land and river run off from urban and agricultural catchments, and are often associated with nutrients and contaminants (Fabricius & Wolanski, 2000; Fabricius *et al.*, 2003). These environmental conditions are generally considered marginal for reef growth, which together with the lack of detailed ecological descriptions of turbid zone reefs (often impeded by limited visibility associated with high turbidity), has lead to inferences that these reefs are degraded and characterised by low coral cover and species diversity (Neil *et al.*, 2002; Woolridge *et al.*, 2006; Jupiter *et al.*, 2008). However, these perceptions are in stark contrast to the often high coral cover and diversity reported on many turbid zone reefs (Veron, 1995; Sweatman *et al.*, 2007; Browne *et al.*, 2010), and the rapid vertical accretion rates (>2 mm/year) calculated for in these environments, these often exceeding those determined in offshore clear-water settings (Perry *et al.*, 2009; Palmer *et al.*, 2010; Perry & Smithers, 2010). These studies suggest that benthic communities on inshore turbid reefs have adapted to high sedimentary regimes and are potentially more robust and resilient than previously thought. However, current understanding of how inshore turbid reefs have grown and developed under marginal environmental conditions is limited, as are predictions of inshore reef resilience to future environmental change.

The accumulation of reef framework required for reef growth is reliant on the balance between carbonate production by calcifying organisms (corals, calcareous coralline algae (CCA), molluscs, crustaceans, bryozoans, foraminiferans, serpulid worms), and carbonate destruction from bioerosion (borers, urchins, fish) and physical destruction (e.g. storm event; Stearn *et al.*, 1977; Hubbard *et al.*, 1990). Carbonate destruction produces carbonate sediments, which are either stored on the reef (Hubbard *et al.*, 1990) or are transported off-reef (Hughes, 1999). The assessment of gross carbonate production, destruction and sediment production is quantified as a reef carbonate budget, and can provide valuable insights into reef growth and development (Edinger *et al.*, 2000). For example, the assessment of the dominant coral taxa and of rates of carbonate production will give an indication of coral community stability and temporal variations in productivity which influence reef growth (Perry *et al.*, 2008a). However, few studies have quantified carbonate budgets for coral reefs in detail, exceptions include Stearn *et al.* (1977), Scoffin *et al.* (1980), Hubbard (1990), Eakin (2001) and Mallela and Perry (2007), all of which were conducted in the Caribbean, a study in Hawaii by Harney and Fletcher (2003), work by Edinger *et al.* (2000) in Indonesia, and by Hart and Kench (2007) in Torres Strait. As of yet, no carbonate budget studies that quantify both production and destruction have been conducted on the Great Barrier Reef (GBR), a reef ecosystem that differs ecologically (species composition), physically (hydrodynamics) and geologically (sea-level history) from those conducted in the Caribbean and in the rest of the Indo-Pacific.

In particular, the role of terrigenous sediments in influencing carbonate budgets, and thus the growth and development of reefs is poorly understood, although has been conceptually modelled by Woolfe and Larcombe (1999). The model depicts the balance between the accumulation of terrigenous sediments on a reef, together with carbonate production and removal to schematically demonstrate how reefs can persist where turbidity is high. Kleypas *et al.* (2001) also recognised the importance of sedimentary processes and defined four reef growth models based on key reef processes (production, import, export, bioerosion), which can be broadly applied to a number of reef types including turbid zone reefs. Both models provide useful insights into reef growth and development in terrigenous sedimentary settings, but remain qualitative due to the lack of detailed data available on both rates of carbonate production and on sedimentary regimes. Assessments of carbonate production and destruction rates, combined with data on sediment import, storage and export, are thus necessary to permit assessments of temporally and spatially variable rates of reef growth. Such reef growth models would also provide novel approaches for assessing how changing environmental conditions, particularly sedimentary regimes, influence long-term reef growth and development.

A number of methods are used to calculate a reef's carbonate budget, including the alkalinity-anomaly technique which is based on assessing spatial variations in water chemistry changes (Smith and Kinsey, 1976; Chisholm & Gattuso, 1991), geological estimates from net carbonate production (Ryan *et al.*, 2001), and the modelling technique which also focuses on net carbonate production and accumulation (Kleypas, 1997). However, the census technique which is based on reef organism cover and calcification rates provides a number of advantages over these techniques (because it is based on individual process measurements) and has, therefore, been the most widely used (Stearn *et al.*, 1977; Scoffin *et al.*, 1980; Hubbard *et al.*, 1990; Mallela & Perry, 2007). It can be applied at the sub-reef scale to determine how carbonate budgets vary between different reef habitats; it evaluates the carbonate contributions from different reef organisms; and it can provide critical information on how environmental changes influence reef organisms, and thus carbonate production at different reef scales and stages of reef growth.

In this paper I use both new and established techniques to quantify carbonate production and destruction together with sediment import, storage and export at a high spatial resolution for Middle Reef and Paluma Shoals (Fig. 1.1). Middle Reef and Paluma Shoals are two turbid zone reefs located approximately 30 km apart on the inner-shelf region of central GBR, and are of comparable size (~0.35 km^2). They are, however, subjected to different hydrodynamic and anthropogenic influences: Middle Reef is relatively sheltered from strong offshore winds and waves, but is more exposed to elevated anthropogenic influences (e.g. dredge events, boating activity), whereas Paluma Shoals is exposed to strong winds and waves but is more distant from, and therefore less impacted by, direct anthropogenic pressures. Net carbonate production is calculated for each reef, and the influence of terrigenous sediments on reef growth and development is evaluated. Estimates of carbonate production and destruction are evaluated with error analysis and compared with published budgets for other reefs. This study represents the first carbonate budget study for the GBR, and the first to incorporate a quantitative analysis of terrigenous sediment dynamics onto, within and off a reef system in the development of a quantitative reef growth model.

8.3 Materials and Methods

Net carbonate production and sediment regimes were calculated for separate reef zones delineated on the basis of reef morphology, depth and benthic cover. Net framework carbonate production was calculated as the gross carbonate framework production less that removed by erosive processes. Measures of gross framework carbonate production were based on the abundance and calcification rates of corals and encrusting organisms (CCA, molluscs, serpulid worms, bryozoans), and removal of carbonate framework was calculated from bioerosion (macro-borers, fish, urchins). Total carbonate sediment production was calculated as the mass of sediment bioeroded from the carbonate framework and the total mass of direct sediment production by molluscs, foraminifera and *Halimeda.* The sediment regime was measured using sediment trays (Browne *et al.*, in review-a), which quantified the mass of sediments (carbonate, non-carbonate) imported into, retained and exported from each reef zone. Reef accretion rates and mode of reef growth were determined from net carbonate framework production and sediment dynamics. These methods are described in detail below and equations used are shown in Table 8.1.

8.3.1 Reef geomorphology, habitat and zone analysis

Reef morphology was mapped using a single beam acoustic depth sounder coupled with a real time kinematic (RTK) GPS to correct for wave and boat movements. The hydrographic survey package HYPACK was used to generate a digital terrain model of each reef from the bathymetric data. Benthic cover surveys were conducted during August – September 2008 on snorkel and SCUBA using 20 m photo transects that were GPS referenced (Hill and Wilkinson 2004). A total of 30 and 29 transect surveys were

Table 8.1: Equations employed in the carbonate budget, sediment dynamics and reef growth models.

Equation	Variable	Symbol	Units	Equation
1	Zone habitat area	A_z	m^2	Planimetric area (m^2) x rugosity
2	Coral carbonate production	CCP	kg/year	Coral cover (%) x A (m^2) x calcification rate (kg/m^2/year)
3	Gross coral carbonate production	G_{cor}	kg/year	∑ CCP (kg/year)
4	Normalised coral carbonate production rate	$G_{cor}N$	kg/m^2/year	G_{cor} (kg/year) ÷ A_z (m^2)
5	Encrusting carbonate production	ECP	kg/year	Encrusting calcification rate (kg/m^2/year) x A_Z (m^2)
6	Gross encrusting carbonate production	G_{enc}	kg/year	∑ ECP (kg/year)
7	Gross carbonate framework production	G_F	kg/year	∑ CCP (kg/year) + ∑ ECP (kg/year)
8	Normalised framework production rate	G_FN	kg/m^2/year	G_F (kg/year) ÷ A_z (m^2)
9	Sediment mass per volume	SED_{VOL}	kg/m^3	Sediment dry weight (kg) ÷ sample volume (m^3)
10	Sediment mass per area	SED_{SA}	kg/m^2	SED_{VOL} (kg/m^3) ÷ sample depth (m)
11	Direct carbonate sediment production	DSP	kg/year	SED_{SA} (kg/m^2) x turnover rate (y^{-1}) x abundance (%) x sediment surface area (m^2)
12	Gross direct carbonate sediment production	G_{DSP}	kg/year	∑ DSP (kg/year)
13	Normalised direct sediment production rate	$G_{DSP}N$	kg/m^2/year	G_{DSP} (kg/year) ÷ A_Z (m^2)
14	Macro-borer sediment production	B_M	kg/year	G_{cor} (kg/year) ÷ %age bioeroded
15	Normalised macro-borer sediment production rate	B_MN	kg/m^2/year	B_M (kg/year) ÷ A_Z (m^2)
16	Urchin sediment production	B_U	kg/year	No. of urchins x erosion rate (kg/year)
17	Normalised urchin sediment production rate	B_UN	kg/m^2/year	B_U (kg/year) ÷ A_Z (m^2)
18	Total bioerosion rate	B_TN	kg/m^2/year	B_MN (kg/m^2/year) + B_UN (kg/m^2/year)
19	Total sediment production	$G_{SP}N$	kg/m^2/year	$G_{DSP}N$ (kg/m^2/year) + B_TN (kg/m^2/year)
20	Imported sediment retention rate	RET	kg/m^2/year	Sed deposition rate (kg/m^2/year) - $G_{SP}N$ (kg/m^2/year)
21	Mass of imported sediments retained	RET_M	kg/year	RET (kg/m^2/year) x A_Z (m^2)
22	Imported carbonate sediment retention rate	RET_{CAR}	kg/m^2/year	(Carbonate accumulated (%) x sediment deposition rate (kg/m^2/year)) - $G_{SP}N$ (kg/m^2/year)
23	Total mass of sediments retained	RET_{TM}	kg/year	∑ RET_M (kg/year)
24	Normalised sediment retention rate	$RET_{TM}N$	kg/m^2/year	RET_{TM} ÷ A_H (m^2)
25	Sediment export rate from zone	EXP	kg/m^2/year	Sediment flux rate (kg/m^2/year)
26	Mass of sediments exported from zone	EXP_M	kg/year	EXP (kg/m^2/year) x A_Z (m^2)
27	Total mass of sediments imported into zone	IMP_M	kg/year	RET_M (kg/year) + EXP_M (kg/year)
28	Total reef sediment export rate	Reef EXP_M	kg/year	Reef $IMP_{TM}N$ (kg/year) (assessed from wave dynamics and reef morphology) - RET_{TM} (kg/year)
29	Carbonate sediment produced *in situ* exported	SP_{EXP}	kg/year	($G_{SP}N$ (kg/m^2/year) - sediment accumulation rate (kg/m^2/year)) x A_Z (m^2)
30	Normalised rate of *in situ* sediment production exported	$SP_{EXP}N$	kg/m^2/year	SP_{EXP} ÷ ∑A_Z (m^2)
31	Net carbonate productivity for each zone	N_F	kg/m^2/year	G_FN (kg/m^2/year) - B_TN (kg/m^2/year) - $SP_{EXP}N$ (kg/m^2/year)
32	Reef accretion	RA	mm/year	((N_F (kg/m^2/year) x carbonate density (kg/m^3))/(100 - reef porosity (%)))*100
33	Estimated time of reef initiation	RI	Years	Reef depth (m) ÷ RA (m/year)
34	Volume of annual reef growth	R_{VOL}	m^3	RA (m/year) x A_Z (m^2)
35	Annual reef void volume	V_{VOL}	m^3	Porosity (%) x R_{VOL}
36	Annual volume of imported sediments retained	RET_{VOL}	m^3	RET_{TM} (kg/year) x sediment density (kg/m^3)

conducted at Middle Reef and Paluma Shoals respectively (see Browne *et al.* 2010 for a detailed methodology). K-means cluster analysis in SPSS (version 17) was used to discriminate reef zones covered by transect surveys on the basis of key variables. Variables were determined using Principle Component Analysis (PCA), and included depth, exposure (windward, central, leeward), benthic cover (hard coral, soft coral, algae, abiotic cover) and sediment composition (fine muddy sediment to coarse gravelly sediment). These variables explained >70% of the variance and delineated ten reef zones at Middle Reef and nine at Paluma Shoals (Fig. 8.1). The planimetric area (m^2) of each zone was calculated using the bathymetric model in ArcGIS, and habitat area (m^2) was calculated by multiplying the planimetric area by the rugosity (Eq. 1). Rugosity was determined using the fine chain method of Hubbard *et al.* (1990).

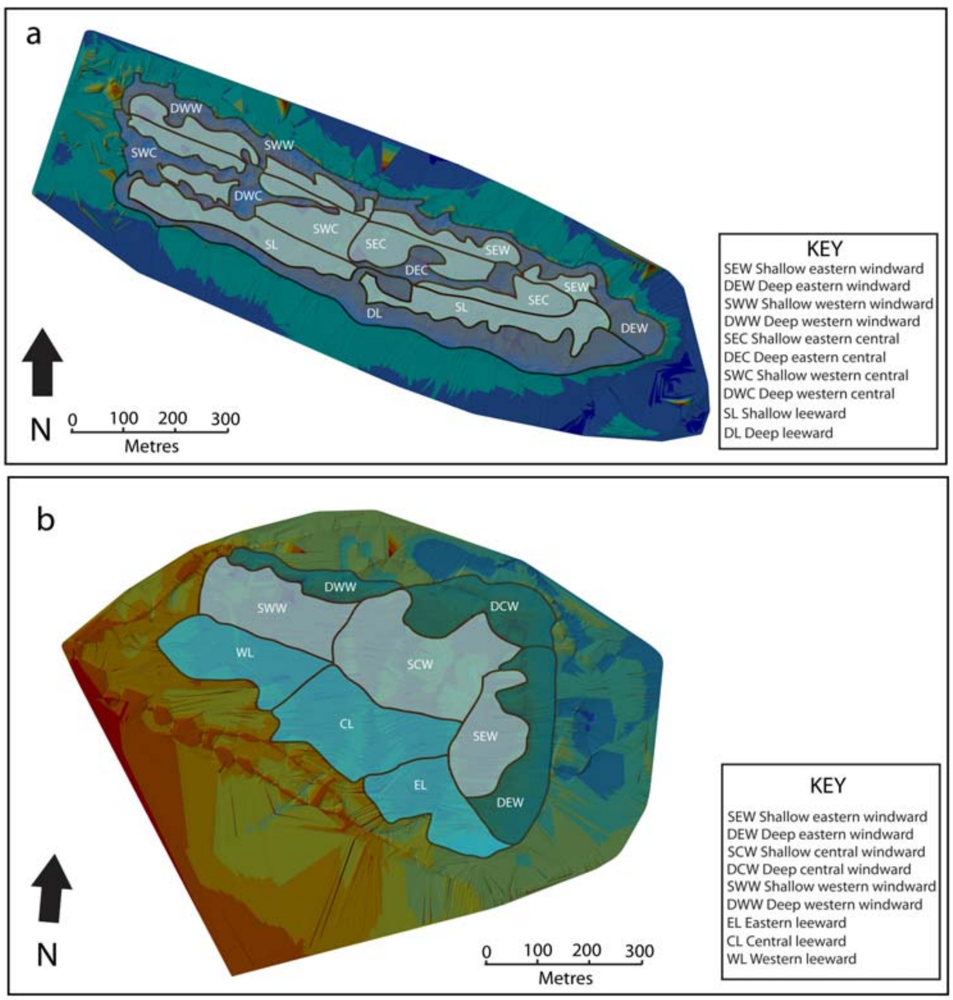

Figure 8.1: Defined boundaries for (a) 10 zones at Middle Reef, and (b) 9 zones at Paluma Shoals. Shallow zones are light blue and deeper zones are dark blue.

8.3.2 Coral carbonate production

Gross coral carbonate production for each zone was calculated by multiplying the calcification rate for each coral by the area that it occupied (coral cover %) in the zone (m^2) (Eq. 2). Calcification rates for *Acropora, Montipora, Turbinaria* were determined *in situ* at Middle Reef by staining corals using Alizarin Red-S (Oliver *et al.*, 1983; Gladfelter, 1984) These corals were common across both reefs, representing 73% of total live coral cover at Middle Reef and 27% at Paluma Shoals. Calcification rates varied over Middle Reef and thus different mean calcification rates were used in each zone (Table 8.2). At Paluma Shoals, calcification rates for *Acropora, Montipora, Turbinaria* were estimated from rates determined within comparable zones at Middle Reef (e.g. deep windward). For the remaining corals, calcification rates were either estimated from rates established in this study (e.g. calcification rates for the foliose coral *Pachyseris* have been estimated from measured calcification rates of *Montipora* and *Turbinaria*) or were sourced from the literature (*Porites, Goniastrea, Favia, Pavona, Galaxea* and *Fungia*; Table 8.3). Where calcification rates were given as either a percentage weight increase (mg/g/day e.g. *Montipora* and *Fungia*) or as a concentration increase per unit area (µmol/cm^2/day e.g. *Porites* and *Galaxea*), rates were estimated from corals with comparable calcification rates. For example, *Porites* produced 0.2 µmol/cm^2/day or 1.72 g/cm^2/day, therefore, *Galaxea* which produces 0.4 µmol/cm^2/day will produce 3.44 g/cm^2/day. The total coral carbonate production (kg/year) was the sum of all carbonate produced by each coral species in each zone (Eq. 3), and a normalised gross carbonate production rate was calculated by dividing the total carbonate produced by the zone area (Eq. 4).

8.3.3 Encrusting organisms carbonate production

Carbonate production by encrusting organisms (CCA, serpulid worms, encrusting bryozoans) was estimated based on the rate of recruitment per unit area over a known time period using ceramic tiles (30 cm by 30 cm). A total of 12 tiles were deployed at 16 sites on Middle Reef and 10 sites on Paluma Shoals for one year. This technique is a suitable method to determine the encrusting community assemblage and carbonate productivity (Martindale, 1992; Mallela, 2007). Tiles were conditioned by soaking in

Table 8.2: Physical and benthic characteristics of geomorphic zones. Mean calcification rates for *Acropora, Montipora* and *Turbinaria* are also provided for each zone.

	Zone characteristics					Coral community cover (%)																Substrate cover (%)			Calcification rates ($g/cm^2/year$)		
Middle Reef						Branching	Plate			Sub-massive		Massive								Solitary							
Geomorphic zone	Zone area (m^2)	Zone rugosity (R)	Habitat area (m^2)	Zone diversity (H')	Live coral cover (%)	*Acropora*	*Montipora*	*Turbinaria*	*Pachyseris*	*Pavona*	*Galaxea*	*Porites*	*Goniastrea*	*Platygyra*	*Goniopora*	*Favia*	*Favites*	*Lobophyllia*	*Symphyllia*	*Fungia*	Other coral	Rubble	Sand	Silt	*Acropora*	*Montipora*	*Turbinaria*
Shallow eastern windward	14,300	1.3	18,161	1.12	9	1	4	2	0	0	0	2	0	0	0	0	0	0	0	0	0	22	20	1	7.2	1.7	6.0
Deep eastern windward	30,000	1.6	48,750	1.23	57	18	24	3	4	0	1	0	0	0	3	0	2	0	0	0	2	13	8	10	5.6	2.3	6.8
Shallow western windward	17,700	1.3	23,010	1.25	28	3	18	1	5	0	0	0	0	0	0	0	0	0	0	0	0	3	5	9	3.6	3.0	6.0
Deep western windward	25,000	1.1	27,167	0.98	62	9	5	0	9	0	1	0	0	0	37	0	0	0	0	0	0	10	8	8	7.3	0.6	6.8
Shallow eastern central	26,000	1.3	32,630	0.55	34	20	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	12	2	7.7	1.4	3.0
Deep eastern central	12,000	1.6	18,900	1.66	56	27	11	7	0	0	0	8	0	0	0	0	0	1	0	0	1	0	20	2	5.1	1.6	2.5
Shallow western central	31,100	1.2	37,631	1.60	41	7	13	0	2	1	0	2	8	3	0	0	0	1	3	0	0	10	7	10	4.1	1.6	4.9
Deep western central	22,000	1.3	28,453	1.04	34	17	14	1	0	0	0	1	0	0	0	0	0	0	0	0	0	7	19	13	6.5	1.3	0.5
Shallow leeward	46,500	1.3	61,070	0.98	28	19	7	1	0	0	0	1	0	0	0	0	0	0	0	0	0	4	16	2	4.9	1.3	6.8
Deep leeward	54,000	1.2	63,360	0.82	55	40	4	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	16	1	2.7	1.3	1.6
TOTAL	**278,600**		**359,132**																								
AVERAGE					**40**	**16**	**11**	**2**	**2**	**0**	**0**	**1**	**1**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**7**	**13**	**6**			
Paluma Shoals																											
Shallow eastern windward	24,600	1.4	33,210	1.19	47	3	1	3	0	0	33	0	1	0	0	0	1	1	1	0	0	6	10	3	7.2	1.7	6.0
Deep eastern windward	34,300	1.1	37,730	1.54	12	2	4	4	0	0	1	0	0	0	0	0	0	0	0	0	0	19	25	1	5.6	2.3	6.8
Shallow central windward	57,300	1.1	63,947	1.15	10	0	0	0	0	0	3	0	4	0	0	0	1	0	0	0	0	15	22	0	3.6	3.0	6.0
Deep central windward	28,700	1.2	33,507	1.02	40	9	2	8	0	0	6	0	0	0	14	0	0	0	0	0	1	5	37	2	7.3	0.6	6.8
Shallow western windward	35,000	1.1	39,988	1.25	25	12	1	1	0	0	1	3	5	1	0	0	1	1	1	0	0	9	23	1	4.1	1.6	5.0
Deep western windward	12,900	1.0	13,094	1.55	26	3	6	2	0	0	11	0	1	0	0	0	1	0	0	1	1	15	22	1	6.5	1.6	0.5
Eastern leeward	29,300	1.1	33,109	0.25	58	0	0	0	0	0	54	0	0	0	3	0	0	0	0	0	0	1	24	7	4.9	1.3	6.8
Central Leeward	46,600	1.2	55,221	1.26	34	2	1	0	0	0	18	2	8	0	0	0	1	0	2	0	1	4	23	4	4.9	1.3	6.8
Western leeward	33,000	1.3	43,340	1.10	20	0	7	1	0	0	0	0	8	1	0	0	1	0	2	1	0	11	22	2	4.9	1.3	6.8
TOTAL	**301,700**		**353,145**																								
AVERAGE					**30**	**4**	**2**	**2**	**0**	**0**	**14**	**1**	**3**	**0**	**2**	**0**	**1**	**0**	**1**	**0**	**0**	**9**	**23**	**2**			

Table 8.3: Summary of published calcification rates from field and laboratory studies

Coral growth form	Genus	Density (g/cm^3)	Extension rate (mm/ year)	Calcification rate (g/cm^2/year)	Extrapolated calcification rate (g/cm^2/year)	Depth range (m)	Region	Source
Branching	*Acropora*	1.03	63	6.31		0 to 4	Middle Reef, inshore, central GBR	Browne *et al.*, 2011
Plate	*Montipora*	0.94	29	1.52		0 to 4	Middle Reef, inshore, central GBR	Browne *et al.*, 2011
				~2 mg/g/day			Laboratory experiment	Jokiel, 1977
	Turbinaria	1.3	10.5	3.75		0 to 4	Middle Reef, inshore, central GBR	Browne *et al.*, 2011
	Pachyseris				2.63		Mean value of *Turbinaria* and *Montipora*	
Massive	*Porites*	1.34	13.4	1.72		3 to 5	Pandora Reef, inshore, central GBR	Lough & Barnes., 2000
		1.25	12.8	1.59		1 to 3	Hannah & Hay Islands, inshore, northern GBR	Cooper *et al.*, 2008
				~2.5		<1	South Thailand	Scoffin *et al.*, 1992
				~0.2 µmol/cm^2/day			Laboratory experiment	Hii *et al.*, 2009
	Platygyra		5 to 12		1.72#		Indo-Pacific	Weber & White, 1974
			16			1 to 2	Dampier Archipelago, Western Australia	Simpson, 1988
	Goniopora				1.72#			
	Goniastrea	1.7	6.8	1.16		5 to 17	Marshall Islands, Pacific Ocean	Highsmith, 1979
	Favia	1.43	5.7	1.07*		2 to 30	Marshall Islands, Pacific Ocean	Highsmith, 1979
		1.4				10	Aqaba	Ramm, 1993
	Galaxea	0.7			3.44		Laboratory experiment	Schutter, 2010
				~0.4 µmol/cm^2/day			Laboratory experiment	Hii *et al.*, 2009
	Pavona	1.44		2		7 to 10	Gulf of Panama	Wellington & Glynn, 1983
Solitary	*Fungia*			*~1 mg/g/day*	*0.76*		Laboratory experiment	Jokiel, 1977

*value used for all other massive corals. # value estimated from *Porites* with comparable skeletal density.

seawater for two weeks prior to deployment on aluminium racks. At each site, there were six exposed tiles (faced upwards) and six cryptic tiles (faced downwards). Of the 192 tiles deployed at Middle Reef and 120 deployed at Paluma Shoals, 142 and 87 were successfully retrieved after one year. Following collection, tiles were dried, soft organisms were removed, and tiles were photographed for analysis in CPCe software to determine the area covered by each encrusting organism. Carbonate production by encrusting organisms was determined by weighing the tile, then soaking it in 5% HCl solution for 48 hours to remove carbonate before rinsing in distilled water. The tiles were then dried at 55^0C and reweighed. The amount of calcium carbonate produced over the year per unit area (g/m^2/year) was calculated by subtracting the weight of the post-treatment tile from the weight of the pre-treatment tile. Control tiles were also weighed, soaked in HCl and reweighed to determine if the ceramic tile lost any mass during treatment; no weight loss was observed. The mean calcification rate was calculated for each zone and used to determine the total mass of carbonate produced by encrusting communities by multiplying the mean calcification rate by zone area (Eq. 5). Data was not available for the deep eastern windward zone at Paluma Shoals as tiles from that zone could not be located due to low visibility. Encrusting carbonate production rates for this zone were estimated using rates from the deep central windward zone.

8.3.4 Gross carbonate production

Gross carbonate framework production (kg/year) for each zone was the sum of the total mass produced by corals (Eq. 3) and encrusting organisms (Eq. 6 & 7). The gross framework production rate (kg/m^2/year) for each zone was calculated by dividing the total mass of carbonate produced by the zone area (Eq. 8).

8.3.5 Direct sediment production

Direct sediment production is the mass of carbonate sediment produced by mollusc, foraminifera and *Halimeda*. Sediment samples were collected from the surface at the start of each transect survey at Middle Reef (30 samples) and Paluma Shoals (29 samples). Sediment samples were collected by hand from an approximately 10 cm by 10 cm area, and depth of sediment removed was noted. Sediment samples were soaked in 5% domestic bleach solution over night to preserve the sediments, oven dried at 55^0C for 24-48 hrs and weighed to determine the sediment mass per sample volume (Eq. 9; g/cm^3). Carbonate content was determined using approximately 5-7 g of the original sample to which 10% HCl solution was added to dissolve the calcium carbonate. After 24 hrs the non-carbonate residue was filtered through a pre-weighed 90 µm filter paper using a suction filter and oven dried at 55^0C for ~4 hrs. Once the filter paper was dry, the paper and the sample were reweighed. Carbonate content was calculated by subtracting the post-dissolved sample from the pre-dissolved sample weight. Sediment type was determined using a binocular microscope (Olympus SZ40, magnification 40X). A sub-sample (~25 g) was dry sieved into five sieve fractions (>2, 1.2-2, 0.85-1.2, 0.4-0.85, <0.4 mm) and composition was assessed by identifying 100 sediment grains for each size class (hard coral, crustose coralline algae, *Halimeda* spp., molluscs, crustacean debris, foraminifera, annelid worms and tube casings, alcyonarians, bryozoans). Sediment composition was expressed as the relative percentage abundance of the total sample and for each of the sieved sub-samples. Total carbonate produced by molluscs, *Halimeda* and foraminiferans (typically the most abundant organisms with the exception of coral fragments) was determined by calculating the sediment mass per unit area (mass per volume divided by the sample depth; Eq. 10) and multiplying the mass per unit area by the organism's turnover rate, abundance (% of sediment sample) and surface area covered by sediment along each transect (Eq. 11). A turnover rate of 1 per year was applied to foraminiferans (Hallock *et al.* 1995), and a turnover rate of 2 per year was applied to molluscs (Kay 1973) and *Halimeda* (Harney 2003). The total direct sediment production for each zone was the sum of the mass produced by each organism (Eq. 12), which was normalised by dividing by the zone area (Eq. 13).

8.3.6 Bioerosion

A total of 87 coral rubble samples were collected from the reef surface at Middle Reef (40 samples) and Paluma Shoals (47 samples). Recently dead coral rubble samples (<1 year) that had a clear corallite structure and little macro-algal growth were selected. Samples were either branching corals (*Acropora)* or plate corals (*Turbinaria* and

Montipora) as these represented species that were fast-growing, ubiquitously distributed and/or quantitatively important on these inshore turbid reefs. Three cross-sections of each rubble sample were used to estimate the percentage bioeroded by macro-borers following Risk *et al.* (1995). Cross-sections were photographed and analysed using the software package CPCe to trace the area removed from the total surface area of the sample. The mean percentage area (%) bioeroded was calculated for each zone, and the total mass bioeroded (kg/year) was calculated as a proportion of the gross carbonate produced using the mean percentage area bioeroded in each zone (Eq. 14). A normalised macro-borer rate for each zone was determined by dividing the amount of carbonate removed by the zone area (Eq. 15). Data was not available for deep western windward and shallow western central zones at Middle Reef where recently dead coral rubble could not be sourced. Bioerosion rates for these zones were estimated using rates from the shallow western windward and deep western central zones.

Bioerosion rates were estimated for fish and urchins using Underwater Visual Census (UVC) data and reported erosion rates (Scoffin *et al.*, 1980). Bioerosion by fish is largely determined from abundance and size distribution of parrotfish, however, no parrotfish were observed during 50 UVC transects conducted between July 2008 and July 2010 at both reefs. *Diadema antillarum* were observed in low numbers (average <1 urchin per transect) at Middle Reef, and the mean size was 60 mm. Reports of bioerosion rates by *Diadema* in size class of 50-60 mm varies globally with rates of approximately 2.3 g of carbonate per day in Barbados (Scoffin, *et al.* 1980), >4 g per day in Moorea in the Pacific (Bak, 1994), and between 0.7 to 1.8 g per day in Kenya (Carreiro-Silva & McClanahan, 2001). In this study, I use rates reported by Scoffin *et al.* (1980) as these are based on the same species of *Diadema* as observed on Middle Reef. The total amount of carbonate framework removed by *Diadema* (kg/year) was calculated by multiplying the mean number of individuals per m^2 for each zone by the erosion rate (Eq. 16). Normalised urchin bioerosion rate was calculated by dividing the amount of sediment removed by the zone area (Eq. 17). The total carbonate framework removed by bioerosion was the sum of macro-borers and urchin bioerosion (Eq. 18).

8.3.7 Sediment dynamics

Sediment accumulation rates estimated from sediment trays were used to calculate the mass of sediments, both carbonate and non-carbonate, imported and exported onto each reef (Browne *et al.*, in review-a). Sediment trays allow for sediment deposition and resuspension and, therefore, assess net sediment deposition per unit area over a known time period to provide a more accurate measure of sedimentation. Four sediment trays were placed in four out of five of the deep zones at Middle Reef. At Paluma Shoals, trays were installed at a deep leeward and windward location, and on the central reef flat (Fig. 6.1). Sediment deposition and accumulation rates were assumed to be the same in both the deep (deeper than 1.5 m) and shallow zones (shallower than 1.5 m) as all sites on both reefs were within the resuspension zone (shallower than 5.5 m) as determined by Wolanski *et al.* (2005) for shallow inshore reefs on the GBR. The rate sediments are imported into the zone (kg/m^2/year) was calculated by subtracting the total carbonate sediment produced in the zone (direct and bioeroded sediment; Eq. 19) from the sediment deposition rate (Eq. 20). The total mass of sediment imported into each zone was calculated by multiplying the sediment import rate by the zone area (Eq. 21), whereas the rate of carbonate sediments imported into the zone was determined by subtracting the mass of carbonate produced *in situ* from the total mass of carbonate on the trays (Eq. 22). The total mass of sediments imported and retained on the reef is the sum of the sediments retained for each zone (Eq. 23), and the sediment retention rate is the total mass imported divided by the total reef surface area (Eq. 24).

Sediment trays were also used to determine the rate sediments were exported from each zone by calculating the sediment flux rate, which represents the total mass of sediments that had been deposited and resuspended in each zone over one year (Eq. 25; see Browne *et al.* in review for methodology). The total mass of sediments exported was calculated by multiplying the rate of sediments exported by the zone area (Eq. 26). Therefore, the total mass of sediments imported into each zone was the sum of that exported and retained (Eq. 27). However, in calculating the rate at which sediments are imported onto the reef, as opposed to a single zone, wave direction was evaluated. At both Middle Reef and Paluma Shoals this was predominantly to the NE (Browne *et al.*, in review-b), and allowed determination of which zone sediments were first transported into. Export rates off the reef were then calculated by subtracting the sum of all zone sediment retention rates from that imported onto the reef (Eq. 28). In zones where the amount of carbonate produced *in situ* was greater than the rate of sediment accumulation, carbonate sediments were being removed. In these zones the rate of sediment removal (sediment production rate minus sediment accumulation rate) was multiplied by the zone area to calculate the mass of carbonate sediment removed (Eq. 29) and was normalised for each zone by dividing by the zone surface area ($SP_{EXP}N$; Eq. 30).

8.3.8 Reef accretion and growth

The net framework productivity for each zone is the gross framework productivity less the bioerosion rate (B_TN) and rate of carbonate sediment removal ($SP_{EXP}N$), if applicable (Eq. 31). The reef accretion rate for each zone is determined by dividing the net framework productivity by the density of carbonate (2.9 g/cm^3) and correcting for reef porosity which is taken as 20% as observed within reef cores extracted from turbid zone reefs on the GBR (Eq. 32; Palmer *et al.*, 2010). The hindcast time of reef initiation was estimated by dividing the depth of the reef by the mean reef accretion rate (Eq. 33).

The mode of reef growth (production, import, export) was determined by assessing whether the reef framework void volume had been filled by imported sediments. Reef accretion rates (cm/year) were converted to m/year and multiplied by the zone area to determine the volume (m^3) of annual reef growth (Eq. 34). The void volume i.e. the porosity, was calculated as a percentage (20%) of the total reef volume within each zone (Eq. 35), and the imported stored sediment volume was calculated by multiplying the mass of sediments retained by the mean sediment density, which for Cleveland Bay is estimated at 2.7 x10^3 kg/m^3 (Eq. 36; Reichelt & Jones, 1994). If the void volume was not filled and net carbonate production was high (>10 kg/m^2/year), reef growth was primarily production dominated; if the void volume was filled due to high sediment retention (>500 x 10^3 kg/year) but production was also high, reef growth was production/import dominated; if the volume of sediments retained surpassed the available void volume, reef growth was primarily import dominated, but if the majority of the void volume was not filled then reef growth was export dominated. Reef growth in each zone was classified in this manner, and together with contemporary reef accretion rates were used to develop a reef growth model. Deep zones were used as a proxy for early reef growth phases, and shallow zones for later reef growth phases. Differences in the mode of reef growth between each of the deep and shallow zones were used to assess how the reef may have developed spatially over time.

8.4 Results

8.4.1 Benthic community description

Middle Reef (278,600 m^2) has lower planimetric surface area than Paluma Shoals (301,700 m^2), but because it is topographically more complex and has a higher reef rugosity, there is little difference in the total habitat surface area (Middle Reef = 359,132 m^2, Paluma Shoals = 353,145 m^2; Table 8.2). The mean coral cover was 40% (SE $\pm$ 4.19) at Middle Reef and 30% (SE $\pm$ 3.94) at Paluma Shoals, but varied between zones at each site. At Middle Reef, coral cover varied from 9% along the shallow eastern windward zone to 62% along the deep western windward zone, and at Paluma Shoals varied from 10% in the shallow central windward zone to 58% long the eastern leeward zone (Table 8.2; Fig. 8.1). At Middle Reef, *Acropora* (16%) and *Montipora* (11%) were the dominant coral species, but *Turbinaria, Pachyseries*, *Porites, Goniastrea* and *Goniopora* were also found in high abundance (>5%) in a few zones. At Paluma Shoals, *Galaxea* (14%) was the dominant coral species, most abundant along the leeward reef margin, and *Acropora, Montipora, Turbinaria, Goniastrea* and *Goniopora* were also abundant (5%).

8.4.2 Coral carbonate production

Total gross annual carbonate production by corals was 5.37 x 10^6 kg at Middle Reef and 3.07 x 10^6 kg at Paluma Shoals (Table 8.4). At Middle Reef, carbonate production was highest (9.8 x 10^6 kg) in the deep eastern windward zone and along the leeward edge (<8.5 x 10^6 kg), whereas the lowest rates (<2 x 10^6 kg) of carbonate production occurred in the shallow eastern and western windward zones. At Paluma Shoals carbonate production was highest (6.3 x 10^6 kg) in the eastern leeward zone, and lowest (<1 x 10^6

Table 8.4: Summary of gross carbonate production, bioerosion, sediment production and net carbonate productivity for each zone and reef.

Zones	**Carbonate production**											**Bioerosion**											**Direct sediment production**				**Sediment export**	**Net carbonate production**
	Gross framework production (kg/year)						Gross framework production G_F (x 10^3 kg/year)		Normalised coral carbonate production rate $G_{cor}N$ (kg/m^2/year)	Normalised encrusting carbonate production rate $G_{enc}N$ (kg/m^2/year)	Normalised framework production rate G_FN (kg/m^2/year)	Macro-bioerosion (%)	Macro-borer sediment production B_M (kg/year)		Normalised macro-borer sediment prod. rate B_MN (kg/m^2/year)	Urchin sediment production B_U (kg/year)		Normalised urchin sediment prod. rate B_UN (kg/m^2/year)	Total bioeroded sediment (x10^3 kg/year)		Total bioerosion rate B_TN (kg/m^2/year)	Gross direct sediment production G_{DSP} (x10^3 kg/year)		Normalised sediment production rate $G_{DSP}N$ (kg/m^2/year)	Total sediment production rate $G_{SP}N$ (kg/m^2/year)	Sediment export rate SP_{EXP} (kg/m^2/year)	Net carbonate productivity N_F (kg/m^2/year)
Middle Reef	**Corals C_{cor}**	**SE**	**Encrusting C_{enc}**	**SE**	**Total G^F**	**SE**	**Total**	**SE**					**Total**	**SE**		**Total**	**SE**		**Total**	**SE**		**Total**	**SE**				
Shallow eastern windward	60,991	2,770	18,671	2,793	79,662	5,563	80	6	3.4	1.0	4.4	6.8	5,436	380	0.3	0	0	0.0	5.4	0.4	0.3	9.3	0.0	0.5	0.8	0.0	4.1
Deep eastern windward	984,231	313,793	54,226	9,880	1,038,457	323,673	1,038	324	20.2	1.1	21.3	9.9	103,220	32,172	2.1	0	0	0.0	103	32.2	2.1	3.9	1.8	0.1	2.2	0.0	19.2
Shallow western windward	200,736	48,709	14,583	2,621	215,319	51,330	215	51	8.7	0.6	9.4	4.9	10,566	2,519	0.5	1,018	1,018	0.04	11.5	3.5	0.5	1.0	0.6	0.04	0.5	0.0	8.8
Deep western windward	441,112	12,018	1,716	546	442,828	12,564	443	13	16.2	0.1	16.3	4.9*	21,730	617	0.8	0	0	0.00	21.7	0.6	0.8	1.5	0.8	0.05	0.8	0.0	15.5
Shallow eastern central	603,176	492,786	26,716	2,793	629,892	495,579	630	496	18.5	0.8	19.3	7.0	43,885	34,527	1.3	0	0	0.00	43.9	34.5	1.3	12.2	0.0	0.4	1.7	0.0	18.0
Deep eastern central	352,127	9,270	6,247	1,381	358,374	10,650	358	11	18.6	0.3	19.0	26.1	93,504	2,779	4.9	313	209	0.02	93.8	3.0	5.0	4.5	2.4	0.2	5.2	0.0	14.0
Shallow western central	298,107	38,371	5,301	1,747	303,407	40,118	303	40	7.9	0.1	8.0	11.6*	35,310	4,669	0.9	1,664	1,664	0.04	37.0	6.3	1.0	1.6	0.8	0.04	1.0	0.0	7.1
Deep western central	411,292	308,033	21,415	7,737	432,707	315,770	433	316	14.4	0.7	15.2	11.6	50,357	36,749	1.8	944	763	0.03	51.3	37.5	1.8	5.9	4.1	0.2	2.0	0.0	13.4
Shallow leeward	678,044	512,359	6,846	3,550	684,890	515,909	685	516	11.1	0.1	11.2	16.1	109,965	82,834	1.8	0	0	0.00	110	82.8	1.8	6.6	3.8	0.1	1.9	0.2	9.2
Deep leeward	851,991	100,154	52,548	29,990	904,540	130,144	905	130	13.4	0.8	14.2	3.0	27,200	3,913	0.4	3,503	2,713	0.06	30.7	6.6	0.5	13.2	7.3	0.2	0.7	0.0	13.8
AVERAGE	**488,181**		**20,827**		**509,008**		**509**		**13.3**	**0.6**	**13.8**							**0.02**			**1.5**			**0.2**	**1.7**		**12.3**
TOTALS (kg/year)	**5,369,988**		**229,095**		**5,599,083**								**501,172**			**7,442**											
TOTALS (10^3 kg/year)	**5,370**		**229**		**5,599**								**501**			**7.4**			**509**			**59.7**					

Table 8.4 continued.

	Carbonate production											Bioerosion										Direct sediment production				Sediment export	Net carbonate production
	Gross framework production (kg/year)						Gross framework production G_F (x 10^3 kg/year)		Normalised coral carbonate production rate $G_{cor}N$ (kg/m^2/year)	Normalised encrusting carbonate production rate $G_{enc}N$ (kg/m^2/year)	Normalised framework production rate G_FN (kg/m^2/year)	Macro-bioerosion (%)	Macro-borer sediment production B_M (kg/year)		Normalised macro-borer sediment prod. rate B_MN (kg/m^2/year)	Urchin sediment production B_U (kg/year)		Normalised urchin sediment prod. rate B_UN (kg/m^2/year)	Total bioeroded sediment (x10^3 kg/year)		Total bioerosion rate B_TN (kg/m^2/year)	Gross direct sediment production G_{DSP} (x10^3 kg/year)		Normalised sediment production rate $G_{DSP}N$ (kg/m^2/year)	Total sediment production rate $G_{SP}N$ (kg/m^2/year)	Sediment export rate SP_{EXP} (kg/m^2/year)	Net carbonate productivity N_F (kg/m^2/year)
Paluma Shoals	**Corals C_{cor}**	**SE**	**Encrusting C_{enc}**	**SE**	**Total G^F**	**SE**	**Total**	**SE**					**Total**	**SE**		**Total**	**SE**		**Total**	**SE**		**Total**	**SE**				
Shallow eastern windward	546,655	243,798	3,778	1,260	550,433	245,058	550	245	16.5	0.1	16.6	19.6	108,006	48,085	3.2	0	0	0.00	108	48.1	3.2	2.6	0.0	0.1	3.3	3.3	10.0
Deep eastern windward	190,756	42,682	1217*	407	191,973	43,089	192	43	5.1	0.03	5.1	12.2	23,390	5,250	0.6	0	0	0.00	23.4	5.2	0.6	8.05	0.4	0.2	0.8	0.8	3.6
Shallow central windward	141,687	46,700	3,353	2,025	145,039	48,726	145	49	2.2	0.05	2.3	17.5	25,429	8,543	0.4	0	0	0.00	25.4	8.5	0.4	14.7	5.4	0.2	0.6	0.6	1.2
Deep central windward	561,016	117,964	1,217	407	562,233	118,371	562	118	16.7	0.04	16.8	18.2	102,403	21,560	3.1	0	0	0.00	102	21.6	3.1	10.6	3.5	0.3	3.4	3.4	10.3
Shallow western windward	286,008	113,217	5,971	936	291,979	114,153	292	114	7.1	0.15	7.3	9.0	26,198	10,242	0.7	0	0	0.00	26.2	10.2	0.7	11.5	4.3	0.3	0.9	0.9	5.7
Deep western windward	97,842	27,105	594	190	98,436	27,294	98	27	7.5	0.05	7.5	10.6	10,405	2,885	0.8	0	0	0.00	10.4	2.9	0.8	3.8	2.6	0.3	1.1	1.1	5.6
Eastern leeward	633,620	286,216	3,857	834	637,478	287,050	637	287	19.1	0.12	19.2	22.3	142,056	63,966	4.3	0	0	0.00	142	64.0	4.3	3.1	2.1	0.1	4.4	0.0	15.0
Central Leeward	488,451	142,356	4,773	958	493,223	143,314	493	143	8.8	0.09	8.9	11.0	54,458	15,824	1.0	0	0	0.00	54.5	15.8	1.0	10.1	2.3	0.2	1.2	0.0	7.9
Western leeward	126,273	52,132	5,117	4,054	131,390	56,186	131	56	2.9	0.12	3.0	17.0	22,292	9,533	0.5	0	0	0.00	22.3	9.5	0.5	13.1	8.8	0.3	0.8	0.0	2.5
AVERAGE	**341,368**		**3,582**		**344,687**		**345**		**9.6**	**0.08**	**9.6**							**0.00**			**1.6**			**0.2**	**1.8**		**6.9**
TOTALS (kg/year)	**3,072,309**		**28,659**		**3,102,185**								**514,636**														
TOTALS (10^3 kg/year)	**3,072**		**29**		**3,102**								**515**						**515**			**77.7**					

*values estimated from nearby sites out of zone due to missing data.

kg) in the deep western windward zone. Gross coral carbonate production when normalised for reef habitat area ranged from 3.4 kg/m^2/year (shallow eastern windward zone) to 20.2 kg/m^2/year (deep eastern windward zone) at Middle Reef, and from 2.2 kg/m^2/year (shallow central windward) to 19.1 kg/m^2/year (eastern leeward) at Paluma Shoals (Table 8.4).

8.4.3 Carbonate production by encrusting organisms

Total annual encrusting carbonate production (exposed and cryptic) was 229 x 10^3 kg at Middle Reef and 29 x 10^3 kg at Paluma Shoals (Table 8.4). When normalised for reef habitat area, encrusting carbonate production ranged from 0.06 kg/m^2/year (deep western windward zone) to 1.11 kg/m^2/year (deep eastern windward zone) at Middle Reef, and from 0.03 kg/m^2/year (deep eastern windward zone) to 0.15 kg/m^2/year (shallow western zone) at Paluma Shoals. Common encrusting organisms included CCA, serpulid worms, bryozoans, molluscs and coral. However, CCA and serpulid worms accounted for 45% and 20% of the encrusting cover at Middle Reef, and 70% and 22% at Paluma Shoals. Of the total carbonate produced by encrusters at Middle Reef, 56% and 66% occurred on the cryptic tiles at shallow and deep sites respectively (Table 8.5), with the largest amount of occurring on cryptic tiles in the deep leeward zone (Fig. 8.2). However, the highest total (exposed and cryptic) encruster carbonate

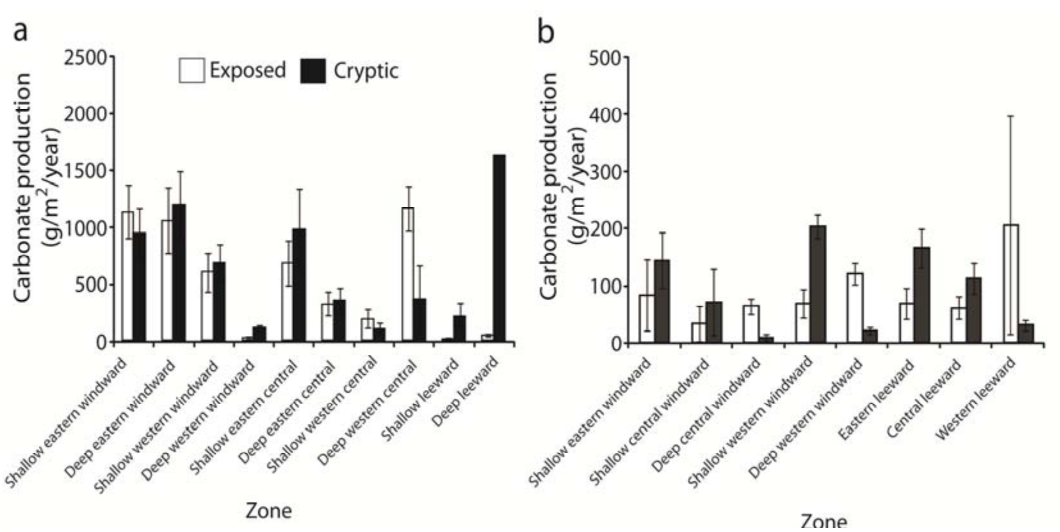

Figure: 8.2: Carbonate production by the encrusting community on exposed and cryptic tiles at (a) Middle Reef and (b) Paluma Shoals. Note different scales used.

Table 8.5: Summary of encrusting carbonate production for each zone at Middle Reef and Paluma Shoals

		Carbonate production rate ($g/m^2/year$)			Mass of carbonate (kg/year)		
Middle Reef	**Habitat area (m)**	**Exposed**	**Cryptic**	**Mean**	**Exposed**	**Cryptic**	**Mean**
Shallow eastern windward	18,161	1,122	935	1,028	20,370	16,972	18,671
Deep eastern windward	48,750	1,045	1,180	1,112	50,944	57,507	54,226
Shallow western windward	23,010	594	674	634	13,663	15,503	14,583
Deep western windward	27,167	18	109	63	480	2,952	1,716
Shallow eastern central	32,630	672	965	819	21,935	31,497	26,716
Deep eastern central	18,900	316	345	331	5,968	6,526	6,247
Shallow western central	37,631	184	97	141	6,941	3,661	5,301
Deep western central	28,453	1,150	355	753	32,727	10,103	21,415
Shallow leeward	61,070	14	210	112	859	12,834	6,846
Deep leeward	63,360	43	1,616	829	2,705	102,391	52,548
			Total production*	**Shallow**	*63,767*	*80,466*	
				Deep	*92,824*	*179,479*	
			%age of production	**Shallow**	**44**	**56**	
				Deep	**34**	**66**	
Paluma Shoals							
Shallow eastern windward	33,210	84	144	114	2,773	4,782	3,778
Shallow central windward	63,947	34	71	52	2,154	4,551	3,353
Deep central windward	33,507	63	9	36	2,124	309	1,217
Shallow western windward	39,988	68	204	149	2,709	8,145	5,971
Deep western windward	13,094	121	20	45	1,581	266	594
Eastern leeward	33,109	68	165	117	2,252	5,463	3,857
Central Leeward	55,221	61	112	86	3,378	6,167	4,773
Western leeward	43,340	206	30	118	8,924	1,311	5,117
			Total production*	**Shallow**	*22,190*	*30,420*	
				Deep	*3,705*	*575*	
			%age of production	**Shallow**	**42**	**58**	
				Deep	**87**	**13**	

production rates (>1 $kg/m^2/year$) occurred in the eastern windward zones, and the lowest rate of carbonate production by encrusters (<0.1 $kg/m^2/year$) occurred in the deep western windward zone (Table 8.4). Of the total carbonate produced by encrusters at Paluma Shoals, 58% occurred on the cryptic tiles at shallow sites and 13% at deep sites (Table 8.5), with the largest amount of carbonate produced on cryptic tiles in the shallow western windward zone (Fig. 8.2). In general, the rate of carbonate production by encrusters along the windward edge decreased with depth on cryptic tiles (average from 0.14 to 0.015 $kg/m^2/year$), and increased with depth on the exposed tiles (0.06 to 0.09 $kg/m^2/year$). Along the leeward reef edge, encruster carbonate production rates were greatest on the cryptic tiles (>0.1 $kg/m^2/year$) at the central and eastern sites, but increased to >0.2 $kg/m^2/year$ on exposed tiles along the western leeward edge.

8.4.4 Gross carbonate production

Total annual gross carbonate production was 5.6×10^6 kg at Middle Reef of which 96% was produced by corals, and 3.1×10^6 kg at Paluma Shoals of which 99% was produced by corals (Table 8.4).

8.4.5 Direct sediment production

Direct sediment production was estimated from the abundance of molluscs, *Halimeda* and foraminiferans in surficial sediment samples. Molluscs were common at Middle Reef and produced between 0.13 to 1.48 $kg/m^2/year$ (Table 8.6). The most productive areas (>1 $kg/m^2/year$) were the eastern windward and shallow central zones, whereas the least productive (<1 $kg/m^2/year$) were the western and leeward zones. On average, molluscan sediment was produced at 0.71 $kg/m^2/year$ which equates to 50.5×10^3 kg each year at Middle Reef. At Paluma Shoals, the average rate of molluscan sediment production was 0.83 $kg/m^2/year$ which equated to 75×10^3 kg per year, but ranged from 0.28 $kg/m^2/year$ in the eastern leeward zone to 1.4 $kg/m^2/year$ in the deep western windward zone. *Halimeda* were not present in all sediment samples, and sediment production was largely confined to the deep leeward zone at Middle Reef and the shallow western windward and leeward zone at Paluma Shoals. In these zones *Halimeda* sediment production ranged from 0.03 to 0.07 $kg/m^2/year$, which equated to 1.4×10^3 kg at Middle Reef and 1.3×10^3 kg at Paluma Shoals. The mean rate of sediment produced by foraminifera was greater at Middle Reef (0.02 $kg/m^2/year$) than at Paluma Shoals (0.01 $kg/m^2/year$), and equated to 7.3 x 10^3 kg per year at Middle Reef and 1.3 x 10^3 kg per year at Paluma Shoals.

8.4.6 Bioerosion

Bioerosion by macro-borers removed 9% of the gross framework at Middle Reef and 17% at Paluma Shoals, which equated to 501 x 10^3 kg/year of carbonate at Middle Reef, and 515 x 10^3 kg/year at Paluma Shoals. When normalised for zone area, bioerosion rates at Middle Reef ranged from 0.3 $kg/m^2/year$ along the shallow eastern windward zone to 4.95 $kg/m^2/year$ within the deep eastern central zone. Bioerosion rates at Paluma Shoals were also low along the shallow central and western windward zones (<0.66 $kg/m^2/year$), and were highest (4.29 $kg/m^2/year$) within the eastern leeward zone.

No urchins were observed at Paluma Shoals, and urchin abundance was low at Middle Reef (0.023 individuals/m^2). A total of 7.4 x 10^3 kg/year of reef framework was removed by urchins at Middle Reef from five (shallow western central, deep eastern central, shallow and deep western central, deep leeward) of the ten zones, with the highest rates of urchin bioerosion occurring in the deep leeward reef zone (0.06 $kg/m^2/year$; Table 8.4). The total amount of gross framework removed by bioerosion (macro-borers and urchins) at Middle Reef was 509 x 10^3 kg/year. Therefore, the total mass of carbonate sediment produced annually from bioerosion and direct sediment production was 568 x 10^3 kg at Middle Reef and 592 x 10^3 kg at Paluma Shoals.

8.4.7 Sediment dynamics

Net annual sediment deposition and accumulation (*in situ* sediment production and imported sediments) varied significantly between the leeward and windward zones ($p<0.05$; Table 8.7). At Middle Reef net sediment deposition rates were comparatively low (<5 $kg/m^2/year$) along the leeward edge and within the reef's western windward

Table 8.6: Direct sediment production.

Geomorphic zone	Mollusc sediment production rate (kg/m²/year)	Mollusc annual sediment production (kg/year)	*Halimeda* sediment production rate (kg/m²/year)	*Halimeda* annual sediment production (kg/year)	Foraminiferan sediment production rate (kg/m²/year)	Foraminifera annual sediment production (kg/year)
Middle Reef						
Shallow eastern windward	1.09	7,884	0.03	188	0.07	1,256
Deep eastern windward	1.31	1,454	0.00	4	0.05	2,405
Shallow western windward	0.13	423	0.00	0	0.00	19
Deep western windward	0.40	1,334	0.00	0	0.01	142
Shallow eastern central	1.48	12,069	0.00	0	0.01	167
Deep eastern central	0.95	4,229	0.00	0	0.02	326
Shallow western central	0.17	1,508	0.00	0	0.00	107
Deep western central	0.45	5,577	0.00	0	0.01	286
Shallow leeward	0.35	6,321	0.00	0	0.00	238
Deep leeward	0.76	9,607	0.07	1,180	0.04	2,393
Average	**0.71**	**50,405**	**0.01**	**1,372**	**0.02**	**7,338**
Paluma Shoals						
Shallow eastern windward	0.50	2,590	0.00	0	0.00	0
Deep eastern windward	0.78	7,783	0.00	0	0.03	268
Shallow central windward	0.85	14,535	0.00	0	0.01	213
Deep central windward	0.81	10,326	0.00	0	0.03	323
Shallow western windward	1.02	10,504	0.07	902	0.01	61
Deep western windward	1.40	3,772	0.00	0	0.02	45
Eastern leeward	0.28	2,949	0.00	12	0.01	153
Central Leeward	0.83	10,011	0.00	0	0.01	125
Western leeward	0.97	12,521	0.03	422	0.01	156
Average	**0.83**	**74,990**	**0.01**	**1,336**	**0.01**	**1,344**

Table 8.7: Summary of sediment dynamics with detailed quantitative data on sediment accumulation rates, sediment input and retention rates, and sediment export rates per zone at Middle Reef and Paluma Shoals.

			Imported sediment incorporated into reef framework					Mobile imported sediment flux		Total mobile and incorporated sediment		
Middle Reef	**Habitat area (m^2)**	**Total *in situ* sediment production rate $G_{SP}N$ ($kg/m^2/year$)**	**Sediment accumulation rate ($kg/m^2/year$)**	**Sediment carbonate content on trays (%)**	**Imported sediment retention rate RET ($kg/m^2/year$)**	**Imported carbonate sediment retention rate RET_{CAR} ($kg/m^2/year$)**	**Imported sediment retained RET_M ($x10^3$ kg/year)**	**Sediment export rate EXP ($kg/m^2/year$)**	**Mass of sediments exported EXP_M ($x10^3$ kg/year)**	**Total mass of imported sediments IMP_M ($x10^3$/kg/year)**	**Percentage of sediment flow over reef incorporated (%)**	***In situ* sediment export rate SP_{EXP} ($kg/m^2/year$)**
Shallow eastern windward	18,161	0.81	8.5	61.6	7.7	4.4	140	235	4,260	4400	3.17	0.00
Deep eastern windward	48,750	2.20	8.5	61.6	6.3	3.0	310	235	11,440	11750	2.62	0.00
Shallow western windward	23,010	0.55	3.0	60.1	2.4	1.2	60	12	280	340	16.28	0.00
Deep western windward	27,167	0.85	3.0	60.1	2.1	0.9	60	12	330	390	14.51	0.00
Shallow eastern central	32,630	1.72	8.5	61.6	6.8	3.5	220	235	7,660	7880	2.81	0.00
Deep eastern central	18,900	5.20	8.5	61.6	3.3	0.0	60	235	4,440	4500	1.38	0.00
Shallow western central	37,631	1.03	22.7	42.8	21.7	8.7	820	14	520	1340	60.98	0.00
Deep western central	28,453	2.01	22.7	42.8	20.7	7.7	590	14	390	980	59.87	0.00
Shallow leeward	61,070	1.91	1.7	26.9	0.0	0.0	0	38	2,330	2330	-0.49	0.19
Deep leeward	63,360	0.69	1.7	26.9	1.0	1.0	60	38	2,430	2490	2.61	0.00
TOTAL (m^2)	**359,132**						**Sediment retention**			**Sediment input IMP_{TM}***	**Sediment export EXP_{TM}**	**Normalised sediment export rate $SP_{EXP}N$**
TOTAL (x 10^3 kg/year)						**RET_{TM}**	**2,320**			**11,750**	**9,430**	**12**
RATE ($kg/m^2/year$)						**$RET_{TM}N$**	**6.5**		**$IMP_{TM}N$**	**32.7**	**26.3**	**0.03**
Paluma Shoals												
Shallow eastern windward	33,210	3.33	0.0	27.9	0.0	0.0	0	235	7,790	7790	0.00	3.33
Deep eastern windward	37,730	0.83	0.0	27.9	0.0	0.0	0	235	8,860	8860	0.00	0.83
Shallow central windward	63,947	0.63	0.0	27.9	0.0	0.0	0	235	15,010	15010	0.00	0.63
Deep central windward	33,507	3.37	0.0	27.9	0.0	0.0	0	235	7,860	7860	0.00	3.37
Shallow western windward	39,988	0.94	0.0	27.9	0.0	0.0	0	235	9,380	9380	0.00	0.94
Deep western windward	13,094	1.09	0.0	27.9	0.0	0.0	0	235	3,070	3070	0.00	1.09
Eastern leeward	33,109	4.38	15.7	21.9	11.3	0.0	370	120	3,980	4350	5.17	0.00
Central Leeward	55,221	1.17	15.7	21.9	14.5	2.3	800	120	6,630	7430	6.54	0.00
Western leeward	43,340	0.82	15.7	21.9	14.9	2.6	650	120	5,200	5850	6.69	0.00
TOTAL (m^2)	**353,145**						**Sediment retention**			**Sediment input IMP_{TM}***	**Sediment export EXP_{TM}**	**Normalised sediment export rate $SP_{EXP}N$**
TOTAL (x 10^3 kg/year)						**RET_{TM}**	**1,820**			**19,790**	**17,970**	**350**
RATE ($kg/m^2/year$)						**$RET_{TM}N$**	**5.2**		**$IMP_{TM}N$**	**56.0**	**50.9**	**0.99**

zones, but were extremely high (>20 kg/m^2/year) within the protected western central zones. At Paluma Shoals sediments did not accumulate within the windward zones but sediment accumulation was high (>10 kg/m^2/year) within the protected leeward zones. In all but one zone (shallow leeward zone) at Middle Reef, *in situ* sediment production rates were lower than sediment accumulation, indicating that imported sediments were being incorporated into the reef framework at a rate ranging from 1 to 21.7 kg/m^2/year (average carbonate content was 48%). These calculations suggest that 2.3 x 10^3 kg of imported sediments are retained on Middle Reef each year. However, in the shallow leeward zone sediments produced *in situ* are exported off reef at a rate of 0.19 kg/m^2/year, removing 11.6 x 10^3 kg of sediments. At Paluma Shoals, *in situ* sediments are exported from the windward zones at a rate of 0.63 to 3.37 kg/m^2/year, which equates to 350 x 10^3 kg of sediment loss per year, whereas imported sediments accumulated at a rate of 11.3 to 14.9 kg/m^2/year along the leeward reef edge (average carbonate content was 17%). This equated to 1.8 x 10^3 kg of imported sediments being retained on Paluma Shoals each year (Table 8.7).

The total mass of sediments imported (IMP_M) into each zone was calculated by adding the volume of sediments exported (derived from the sediment tray flux rates) from each zone (EXP) to the volume of imported sediments retained in each zone (RET_M; Table 8.7). Sediment import rates and data on wave and current direction (Browne *et al.*, in review-a) were then used to develop a sediment dynamics model over the reef which provides quantitative data on the mass of sediments moving to, within and from each zone (Fig. 8.3). From this model, total sediment input and export on the reef was calculated. Total annual sediment input to the eastern end of Middle Reef was 11.7 x 10^6 kg of which 9.4 x 10^6 kg was exported at the western end of the reef. At Paluma Shoals, the total annual sediment input to the windward north-eastern end was 19.8 x 10^6 kg of which 18 x 10^6 kg was exported from its western leeward margin each year.

8.4.8 Reef accretion and growth models

Mean net carbonate productivity was 12.3 kg/m^2/year at Middle Reef and 6.9 kg/m^2/year at Paluma Shoals (Table 8.4). Lowest net productivity at Middle Reef occurred in the shallow eastern windward zone (4.1 kg/m^2/year) and highest net

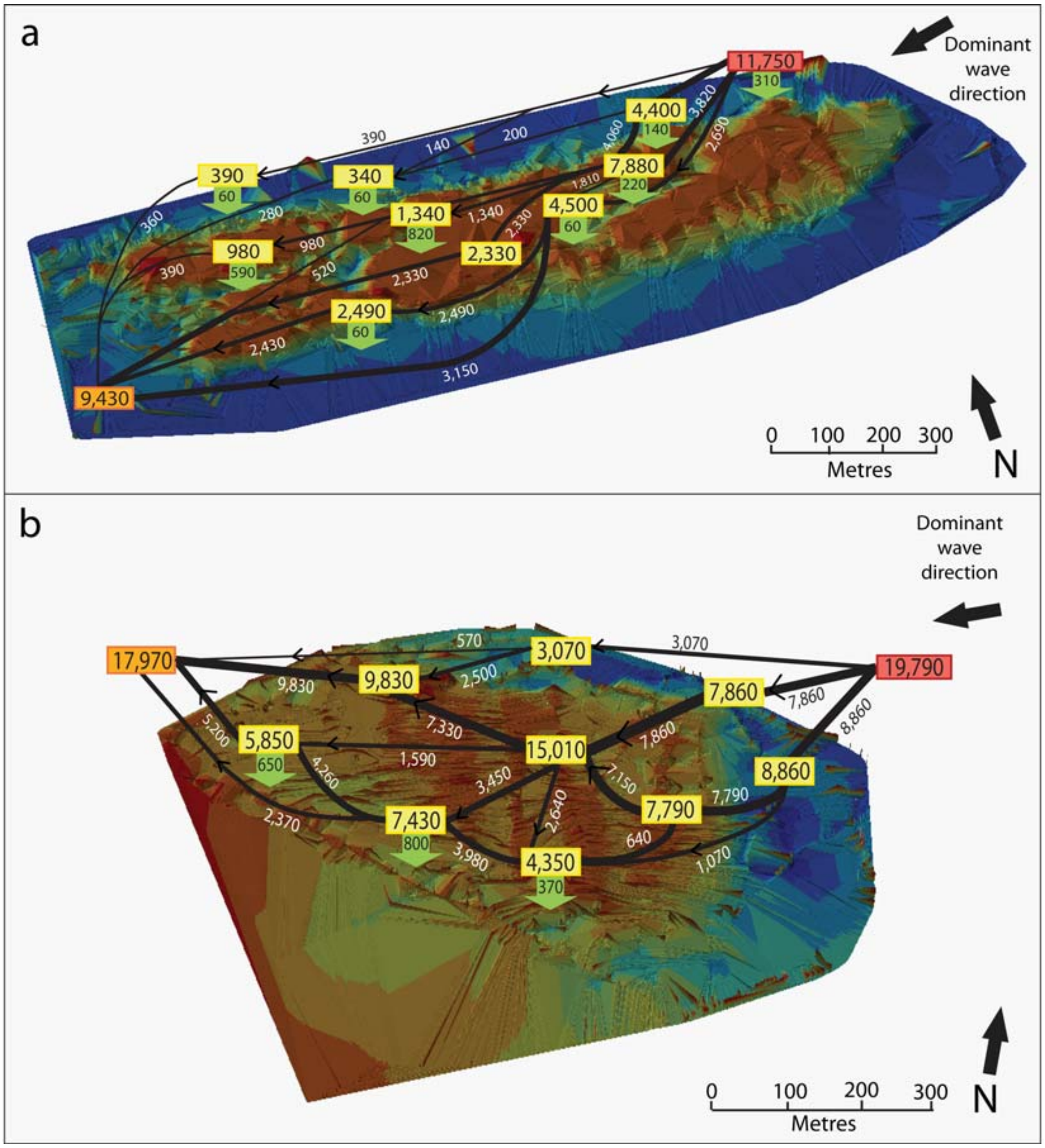

Figure 8.3: Sediment dynamics model for (a) Middle Reef and (b) Paluma Shoals overlaid on to a bathymetric image of the reef structure. The model quantifies sediment input on to the reef (red box), and into each zone (yellow box), sediment transport (black arrows), deposition (green arrows) and export from the reef (orange box).

productivity in the deep eastern windward zone (19.2 kg/m^2/year). At Paluma Shoals, the shallow central windward zone had the lowest net carbonate productivity (1.2 kg/m^2/year) and highest occurred in the eastern leeward zone (15 kg/m^2/year). The mean net carbonate productivity was converted to reef accretion rate which took into account reef porosity and carbonate density (Eq. 32). The reef accretion rate was 5.2

mm/year at Middle Reef and 3 mm/year at Paluma Shoals. Once the reef accretion rate had been calculated, estimates of reef age were made by determining how long it would take the reef to grow from the sea floor to the current depth of the reef flat surface (Eq. 33). At Middle Reef it was estimated that with reef growth rates averaging 5.2 mm/year it would take ~790 years for the reef to reach sea level, whereas at Paluma Shoals it would take ~1,190 years at 3 mm/year (Table 8.8). However, net carbonate production, and therefore reef accretion, varied spatially: at Middle Reef, reef accretion rates ranged from 1.8 mm/year in the shallow eastern windward zone to 8.3 mm/year in the deep eastern windward zone (8.3 mm/year), and at Paluma Shoals, reef accretion rates ranged from 0.5 mm/year in the shallow central windward zone to 6.4 mm/year in the eastern leeward zone. Spatial variations in reef accretion rates and the mass of imported sediments retained were thus used to classify the mode of reef growth for each zone (production, import, export; Table 8.8), and together with the estimated reef age were used to construct a reef growth model with depth and time described in detail below (Fig. 8.4).

Middle Reef

The deep eastern central zone was used as a proxy for the initial stages of reef development with a rapid vertical accretion rate of 6 mm/year occurring due to high rates of carbonate production. At this rate, Middle Reef would have reached 3 m below sea level approximately 670 yr BP, and formed a reef structure that would influence sediment transport processes. The windward edge would have been characterised by increased sediment deposition and accumulation resulting in increased vertical accretion rates (8.3 mm/year). However, contemporary data from the deep leeward zone indicates that due to both high sediment import and export rates, carbonate production would be low and, therefore, reef accretion rates decreased on the leeward edge to 4.9 mm/year. By approximately 550 yr BP, the reef reached 2 m below sea level where the high rate of sediment deposition and accumulation hindered carbonate production and vertical accretion rates fell to 5.8 mm/year. Vertical accretion rates continued to fall to 3.8 mm/year between 1 to 0.5 m below sea level as observed in the shallow western central zone. At 0.5 m depth (~250 yr BP), carbonate production increased, but due to export processes, vertical accretion rates only increased marginally (4 mm/year) until the reef reached sea level approximately 125 yr BP. Reef growth today is rapid within the

Table 8.8: Reef accretion rates, volume of reef growth available annually for sediment infilling, and the mode of reef growth have been estimated for each zone at Middle Reef and Paluma Shoals. In addition, a brief summary of the community assemblage found within each zone are provided.

		Reef accretion		Volume of reef growth and sediments				Reef growth mode		
MIDDLE REEF	Habitat area (m^2)	Net carbonate productivity N_F (kg/m^2/year)	Reef accretion rate RA (mm/year)	Volume of annual reef growth R_{VOL} (m^3)	Annual reef void volume V_{VOL} (m^3)	Imported sediment retained RET_M (x10^3 kg/year)	Annual volume of imported sediments retained RET_{VOL} (m^3)	Infilling	Growth mode	Community assemblage
Shallow eastern windward	18,161	4.09	1.8	32.7	6.5	140	51.7	+	Low production/import	*Acropora/Montipora* dominated
Deep eastern windward	48,750	19.18	8.3	404.6	80.9	310	114.8	+	Production/import	*Acropora/Montipora* dominated
Shallow western windward	23,010	8.83	3.8	87.4	17.5	60	22.2	0	Low production	*Montipora* dominated
Deep western windward	27,167	15.50	6.7	182.0	36.4	60	22.2	-	Production/export	Massive and plate corals
Shallow eastern central	32,630	17.96	7.7	251.3	50.3	220	81.5	+	Production/import	*Acropora/Montipora* dominated
Deep eastern central	18,900	13.99	6.0	113.4	22.7	60	22.2	0	Production	High cover and diverse
Shallow western central	37,631	7.05	3.0	112.9	22.6	820	303.7	+++	Import	Sediment tolerant community
Deep western central	28,453	13.38	5.8	165.0	33.0	590	218.5	++	Import/production	*Acropora/Montipora* dominated
Shallow leeward	61,070	9.23	4.0	244.3	48.9	0	0.0	--	Export/production	*Acropora* dominated
Deep leeward	63,360	13.79	4.9	310.5	62.1	60	22.2	-	Production/export	*Acropora* dominated
Total (m^2)	359,132									
Average			**5.20**							
Depth (m)			**4.20**							
Reef initiation RI (yr BP)			**790**							
PALUMA SHOALS										
Shallow eastern windward	33,210	9.99	4.3	142.8	28.6	0.00	0.0	-	Production/export	Massive and plate corals
Deep eastern windward	37,730	3.63	1.6	60.4	12.1	0.00	0.0	-	Export	Low coral cover
Shallow central windward	63,947	1.24	0.5	32.0	6.4	0.00	0.0	-	Low production/export	Massive corals
Deep central windward	33,507	10.35	4.5	150.8	30.2	0.00	0.0	-	Production/export	Massive and plate corals
Shallow western windward	39,988	5.70	2.5	100.0	20.0	0.00	0.0	-	Export/production	*Acropora* dominated
Deep western windward	13,094	5.64	2.4	31.4	6.3	0.00	0.0	-	Low production/export	Mixed coral community
Eastern leeward	33,109	14.96	6.4	211.9	42.4	370	127.6	+	Production/import	*Galaxea* dominated
Central Leeward	55,221	7.95	3.4	187.8	37.6	800	275.9	+++	Import/production	Sediment tolerant community
Western leeward	43,340	2.52	1.1	47.7	9.5	650	224.1	+++	Import	Sediment tolerant community
Total (m^2)	353,145									
Average			**2.97**							
Depth (m)			**3.50**							
Reef initiation RI (yr BP)			**1,190**							

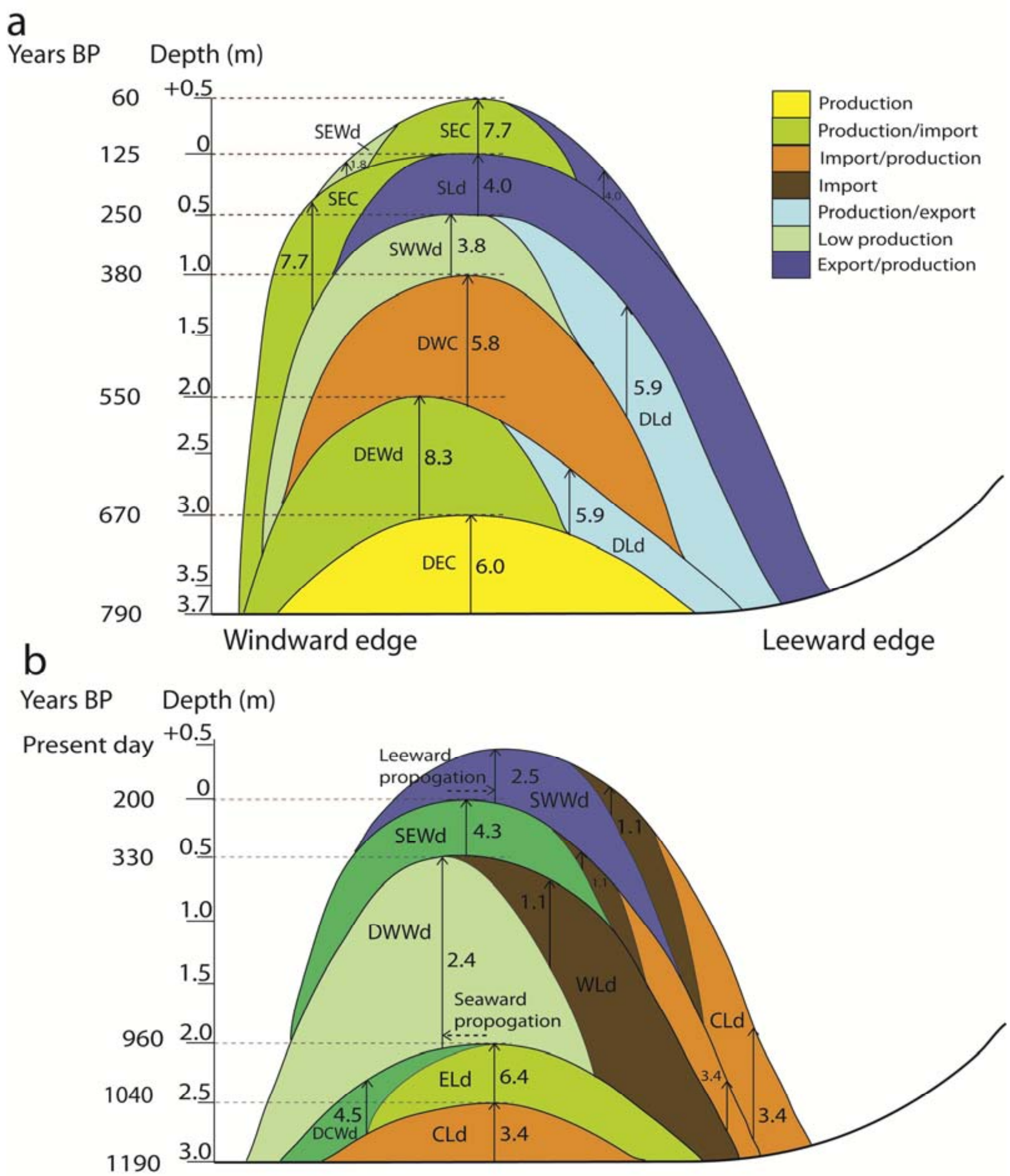

Figure 8.4: Reef growth model for (a) Middle Reef and (b) Paluma Shoals. The model is based on spatially variable contemporary reef growth rates to provide a time line of reef growth. The contemporary zone used is indicated for each stage of reef growth (S=shallow, D=deep, E=eastern, W=western, C=central, Wd=windward, Ld=leeward). Furthermore, the model highlights the dominant reef processes and illustrates how reef processes vary both spatially and temporally.

central regions of the reef (7.7 mm/year), but slower on the shallow leeward edge where high import and export processes may impede coral growth and carbonate production (4 mm/year), and limited on the exposed shallow eastern windward edge where carbonate production is low (1.8 mm/year).

Paluma Shoals

Reef growth in the central leeward zone is taken as a proxy for the first stage of reef growth at Paluma Shoals where the vertical reef accretion rate was 3.4 mm/year due to import/production processes. At this rate, Paluma Shoals would have reached 2.5 m below sea level approximately 1,040 yr BP. The next stage of reef growth was anticipated to be characterised by increased rates of carbonate production, as observed on the eastern leeward edge and characterised by rapid vertical accretion rates (6.4 mm/year), resulting in the reef reaching 2 m depth by approximately 960 yr BP. However, as the reef grew, it created a greater barrier to sediment transport resulting in high sediment deposition and resuspension, as observed within the deep windward zones, which may have impeded coral growth and carbonate production. The net result of this would have been a reduction in the vertical accretion rate (2.4 mm/year) on both the windward and leeward edge (1.1 mm/year). By ~330 yr BP the reef reached 0.5 m below sea level where limited sediment deposition occurred due to increased sediment resuspension rates. This may have permitted an increase in coral growth and carbonate production, and thus increased vertical accretion rates (4.3 mm/year) as observed in the shallow eastern windward zone. On reaching sea level approximately 200 yr BP, reef growth fell from 4.3 to 2.5 mm/year due to high export processes, although high sediment accumulation on the leeward edge resulted in leeward reef propagation and reef flat formation which has now reached ~ 0.5 m above LAT.

8.5 Discussion

8.5.1 Coral carbonate production and destruction

Gross carbonate production on Middle Reef (13.8 kg/m^2/year) and Paluma Shoals (9.6 kg/m^2/year) was high compared to that calculated for reefs elsewhere (Table 8.9). In the Caribbean gross carbonate production rates ranged from 1.2 to 9.6 kg/m^2/year, and

Table 8.9: A summary of carbonate budget assessments from the Caribbean and Asia, and carbonate production from the GBR. Additional studies on sediment dynamics have been included to illustrate differences between sediment dynamics measured in this study to previous studies.

Study site					Carbonate budgets							Sediment dynamics					Reef growth	
Region/country	**Reef**	**Site description**	**Reef area A_H (m^2)**	**Mean coral cover (%)**	**Coral carbonate production G_{COR} (kg/m^2/year)**	**Encrusting carbonate production G_{ENC} (kg/m^2/year)**	**Gross carbonate production G_F (kg/m^2/year)**	**Urchin bioerosion rate B_UN (kg/m^2/year)**	**Bioerosion B_TN (kg/m^2/year)**	**Net carbonate production N_F (kg/m^2/year)**	**Direct sediment production rate $G_{DSP}N$ (kg/m^2/year)**	**Sedimentation rates (kg/m^2/year)**	**Sediment input $IMP_{TM}N$ (kg/m^2/year)**	**Sediment export $EXP_{TM}N$ (kg/m^2/year)**	**Sediment retention $RET_{TM}N$ (kg/m^2/year)**	***In situ* sediment export rate $SP_{EXP}N$ (kg/m^2/year)**	**Accretion rate RA (mm/yr)**	**References**
Central GBR	Middle Reef	Inshore patch reef	359,132	40	13.26	0.58	13.84	0.02	1.51	12.3	0.19	30 to 74	32.7	26.3	6.3	0.03	5.2	This study
	Paluma Shoals	Inshore land-attached reef	353,145	30	9.56	0.08	9.64	0	1.62	6.9	0.22	11 to 122	56	50.9	5.2	0.99	3	
Northern GBR	Green island	Reef flat and slope	1,690,000	5.5 to 16	10		12.7				2.4 to 2.7							Yamano, 2000
Torres Strait	Warraber Island	0-4 m deep inter-tidal reef flat	10,462,700				1.66											Hart & Kench, 2006
Rio Bueno, N. Jamaica		Turbid site		16	1.83	0.05	1.87	0.008	0.265	1.87		28 to 81					1.11	Mallela & Perry, 2007,
		Clear water site		13	1.02	0.2	1.22		0.126	1.23		17 to 35					0.73	Mallela, 2007
St Croix, Virgin Islands	Cane Bay	Fringing reef 2-60 m	30,000	18			1.9											Sadd, 1984
			412,200	14	1.13	0.02	1.21		0.65	0.91	0.06		1.2	0.82	0.38		0.73	Hubbard *et al.*, 1990
												~5						Gleason, 1998
Hawaii	Kailua Bay	Fringing reef to 25 m	9,968,000	32	0.71	0.51	1.22		0.33	0.89	0.2						0.6	Harney & Fletcher, 2003
La Saline Reef, La Reunion		Reef flat							5.6	8.3								Conand *et al.*, 1997
		Back reef							0.4	-1.5								
Barbados	Bellairs Reef	5 m deep fringing reef	10,800	37			15	5.3										Stearn *et al.*, 1980
		<10 m			7.1	2.5	9.6		6.72	4.5							3	Scoffin, 1980
Jamaica	Discovery Bay	0-60 m		25	2.4	2.8	5.2		4.1	1.1				1.2			3	Land, 1979
														6				Meaney, 1973
												15 to 30						Macdonald & Perry, 2003
												1.5 to 4						Dodge, 1974
Panama (<1995)	Uva Island	Back reef	200	54	2.95	0.6	3.83		6.41	0.39					2.97	0.19		Eakin, 1996
		Reef flat	13,655	8	0.42	1.71	2.63		4.83	0.11					2.31			
		Fore-reef	9,491	57	3.1	0.72	4.61		8.29	0.08					3.77			
		Reef base	1,962	0.2	0.01	1.67	3.79		13.64	-3.65					6.21			
Java sea reefs, Indonesia	Gosong Cemara	Submerged coral cay <25 m		69	14.3	not measured	14.3		2.62	11.68		~ 13						Edinger, 2000
	Palau Kecil	Coral cay island <25 m		62	13.5		13.5		2.31	11.19		~ 7						
	Lagun Marican	Mangrove fringe 4 m		24	3.4		3.4		0.89	2.51								
	Bondo	Fringing reef <5 m		28	4.3		4.3		5.09	-0.79		~140						
	Palau Pandang	Coral cay island <8 m		21	3.2		3.2		10.08	-6.88		~100						
South Thailand	Phuket	Fringing reef 2-8 m					3					120 to 200						Scoffin 1997

in Indonesia ranged from 3 to 4.6 kg/m^2/year on turbid and/or anthropogenically impacted reefs. Rates comparable to Middle Reef and Paluma Shoals had only been measured on reefs in Indonesia considered to be 'pristine' where coral cover was >60% (Edinger *et al.*, 2000), and on Green Island in Australia despite low coral cover (16%) and anthropogenic pressures (Yamano *et al.*, 2000). Coral carbonate production was high due to high coral cover (>30%), which contributed over 96% of the carbonate, and high calcification rates for the fast-growing corals, in particular *Acropora* which had a mean calcification rate of 6.4 g/cm^2/year (maximum 19 g/cm^2/year; Browne, in review). Indeed, calcification rates are comparable to clear-water offshore reefs (Oliver *et al.*, 1983) despite high turbidity, and probably occurs as a function of the heterotrophic feeding capabilities of corals on inshore turbid reefs (Stafford-Smith & Ormond, 1992; Gleason, 1998; Anthony, 2000). This enables them to survive and calcify rapidly in low light conditions. Carbonate production rates by the encrusting community at Middle Reef and Paluma Shoals was low (<4% of total carbonate framework produced) compared to coral carbonate production, but is still comparable to rates reported from both clear and turbid water reefs in the Caribbean and Asia (Table 8.9). This suggests that high sediment loads inshore may not be as detrimental to encrusting communities as generally considered (Fabricius & De'ath, 2001; Fabricius & McCorry, 2006). CCA was the dominant encrusting carbonate producer, and over half the carbonate produced by encrusters occurred on cryptic tiles, highlighting the importance of cryptic communities which may be missed during ecological surveys.

Bioerosion and carbonate removal was largely the result of macro-borers as grazing pressure was low at Middle Reef and not observed at Paluma Shoals. Bioerosion influences the rate of reef growth and can play a significant role in sediment production (Hutchings, 1986; Perry, 1998, 1999). Bioerosion rates vary considerably from inshore to offshore reefs (Sammarco & Risk, 1990; Cooper *et al.*, 2008b), with higher macro-boring rates and lower grazing rates inshore, and lower macro-boring rates and higher grazing rates offshore (Hutchings *et al.*, 2005b). At Middle Reef and Paluma Shoals, bioerosion rates were low (<1.62 kg/m^2/year) compared to previous assessments for carbonate budgets (Table 8.9), and were comparable to those estimated for a mid-shelf clear-water reef at Lizard Island (0.22 to 2.71 kg/m^2/year) using experimental coral substrates (Kiene, 1985). Bioerosion rates were low despite anthropogenic pressures and high sediment loads, potentially due to the burial and, therefore, lack of suitable substrates available for boring. Bioerosion removed <17% of the gross carbonate produced by corals and, therefore, net carbonate framework production remained high; at Middle Reef 12.3 kg/m^2/year of carbonate was added to the framework, and 6.9 kg/m^2/year at Paluma Shoals.

8.5.2 Direct sediment production

The importance of molluscs, foraminifera and *Halimeda* sediment production to carbonate budgets, reef growth and development is poorly understood. Where detailed studies have been conducted on sediment production rates, many have found that organisms such as foraminifera and *Halimeda* contribute significantly to sediment mass (e.g. foraminifera contributed 30% of total sediments on Green Island; (Yamano *et al.*, 2000). However, direct sediment production at Middle Reef (1.7 kg/m^2/year) and Paluma Shoals (1.84 kg/m^2/year) was a small contribution to total carbonate production. Bioerosion produced 89% of carbonate sediments, and only 11% was produced by molluscs, foraminifera and *Halimeda.* Molluscs were the main direct sediment producers (25%), which are often found in greater numbers in muddy substrates (Masse, Thomassin *et al.* 1989). Direct sediment production rates established at Middle Reef and Paluma Shoals (0.19 to 0.22 kg/m^2/year) were comparable to those determined on the Kailua Bay fringing reef (0.2 kg/m^2/year; Harney & Fletcher, 2003), but considerably less than sediment production rates determined for the reef flat and slope at Green Island (2.4 to 2.7 kg/m^2/year; Yamano *et al.*, 2000) where foraminifera derived sediment production was high (186,287 per m^2). Given high carbonate framework production and high sediment import rates, direct sediment production is not an important process to both carbonate production and sediment dynamics, and, therefore, reef accretion and growth.

8.5.3 Sediment dynamics

Sedimentation rates varied spatially and temporally at Middle Reef and Paluma Shoals, ranging from 1-122 g/m^2/day, and turbidity regularly fluctuates to >20 NTU due to wind-driven resuspension (Browne *et al.*, in review-b). This study provides the next step in the assessment of sediment regimes by quantifying sediment transport on, within and off a reef, and illustrates that sediment transport is the dominant process, far exceeding rates of sedimentation and accumulation. The total annual mass of sediments imported to Middle Reef was estimated at 11.7 kg x 10^6 kg (90 g/m^2/day) and to Paluma Shoals at 19.7 x 10^6 kg (150 g/m^2/day), of which 19% and 9% were retained on each reef. Previous modelling of sediment transport in Cleveland Bay suggests that 21.5 x 10^6 kg of sediments are transported annually through the Western Channel (Lambrechts *et al.*, 2010). Modelling studies have not been conducted near Paluma Shoals, although Larcombe and Costen (2001) calculated that if total suspended sediment load were to settle on the reef surface when the concentration of suspended sediments was 100 mg/L, 300 g/m^2/day would be deposited. Sediment concentrations of 100 mg/L have been estimated to occur for approximately 34% of the year (Larcombe *et al.*, 2001), but are likely to be considerably higher during the wet summer months when extreme turbidities >200 mg/L (600 g/m^2/day) may occur. However, it is unlikely that all sediments would settle out of the water column given typical wind and wave conditions, and hence our estimate of 150 g/m^2/day at Paluma Shoals is feasible. Whilst Paluma Shoals is subjected to a greater mass of mobile sediments than Middle Reef, it retains a smaller proportion of imported sediments due to higher wave activity which resuspends sediment. The data infers that these resuspended sediments are transported onshore resulting in a higher mass of mobile sediment at Paluma Shoals.

High sediment export rates suggest that sedimentation is potentially less of a threat to benthic communities than generally considered on turbid zone reefs. Net sediment deposition and accumulation was high (>15 kg/m^2/year) in only 5 out of 19 zones at Middle Reef and Paluma Shoals. At Middle Reef, >500 x 10^3 kg of sediment per year were retained in the western central zones which were protected from SE waves. In these zones sediments were deposited as thick layers of fine sediments in between corals and on coral surfaces. However, these zones represented 18% of the total reef habitat area indicating that sediment burial of reef benthos is limited to a relatively small proportion of the reef area. At Paluma Shoals, between 370 x 10^3 kg to 800 x 10^3 kg of sediments per year were retained along the leeward edge within deeper ‘pools’ (> -1 m at LAT) that lay between large strands of *Galaxea* and *Porites,* and below the wave base and resuspension window during both the low and rising tide (Fig. 8.5). The leeward zones represented approximately a third of the total reef habitat, however, the windward edge and reef flat were not threatened by sedimentation and accumulation.

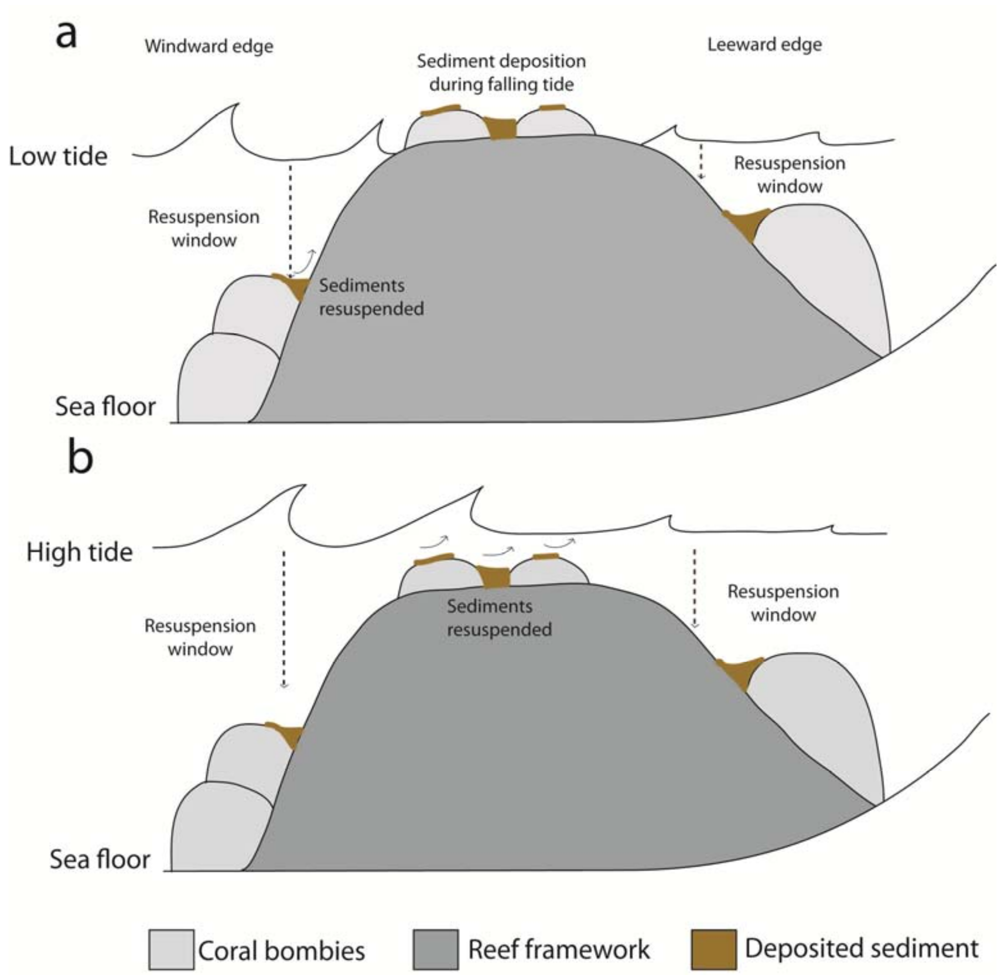

Figure 8.5: Spatial and temporal variations in resuspension windows. During (a) low tide, wave energy resuspends sediments at deeper sites on the windward edge than during (b) high tide. In contrast, wave energy on the leeward edge is low due to reef morphology and, as such, the resuspension window does not extend down to the same depths as on the windward edge, and sediments remain *in situ*. Sediments deposited on the reef flat during the falling tide are resuspended on the rising tide.

The continual accumulation of sediments within protected zones is prevented by strong wind events such as category 1 to 2 tropical cyclones which return every 5 to 10 years to the region (Larcombe and Carter, 2004). Episodic high energy storms which generate larger waves (>3 m) than those observed in 2009/2010 (<2 m) would result in the resuspension of sediments at deeper sites and within protected zones. For example, following Cyclone Yasi in February 2011, no sediment accumulation was observed on the sediment trays in the deep western central zone contrasting to the previous year where approximately 400 g of sediment had accumulated over the wet summer months (Dec to Feb). The removal of 400 g of sediment equates to approximately 6.7 kg/m^2 of sediment deposition (a layer approximately 2.4 mm thick) over 3 months, and given sediment cover is 17 % of the zone area (31,100 m^2), equates to at least an extra 35 x 10^3 kg of sediment removal from this zone during the event. These data suggest that in reef habitats below the wave base which are characterised by high sediment accumulation, high energy events can remove excess sediment and prevent reef framework burial.

8.5.4 Reef accretion rates and growth models

The average reef accretion rates estimated from net carbonate productivity on Middle Reef and Paluma Shoals was 5.3 mm/year and 3.0 mm/year respectively, with hindcast projections for reef initiation suggesting initiation occurring at approximately 790 yr BP at Middle Reef and around 1,190 yr BP at Paluma Shoals. Detailed reef growth studies at Paluma Shoals have estimated reef vertical accretion rates from reef cores between 1.1 and 2.3 mm/year (Palmer *et al.*, 2010), with reef initiation having been shown to have occurred at approximately 1,200 yr BP (the hindcast initiation projected in Smithers & Larcombe, 2003; Perry *et al.*, 2008b). These reef growth and reef initiation estimates are remarkably consistent with this study and suggest that net carbonate production rates and, therefore, coral community composition, have been relatively stable since reef initiation despite recent anthropogenic activities. Recent, but as yet unpublished reef core and radiometric data from Middle Reef (Perry *et al.*, in prep) also indicate a high degree of consistency between the projections calculated in this study and reef growth data determined from radiocarbon dating, with reef initiation occurring between 600 to 700 yr BP, and reef growth reaching sea level within the last 100 yrs.

Contemporary carbonate production and reef accretion rates are greater at Middle Reef due to a higher coral cover of which approximately 60% is due to the rapidly calcifying coral *Acropora*. Rates may also be lower at Paluma Shoals due to higher rates of sediment removal, particularly along the windward edge and reef flat, which would reduce the rate of framework infilling. Nevertheless, these results suggest that both Middle Reef and Paluma Shoals have undergone rapid vertical accretion due to high carbonate productivity from corals.

Turbid zone reef growth is controlled by both carbonate production and terrigenous sediment input as well as variable reef processes (production, import, export, bioerosion). However, until now the relationship between these components has remained largely qualitative and reef growth has been based on conceptual models. Zones at Middle Reef and Paluma Shoals were classified as either dominated by production, import, export or a combination of processes following quantitative analysis of both carbonate production and sediment inputs. Bioerosive processes did not dominate any of the zones given the high gross carbonate productivity on both reefs and comparatively low level of bioerosion. The spatial variability in key processes demonstrates how the physical environment can vary over small-spatial scales within individual reefs, generating reef habitats characterised by varying sedimentary regimes and different community assemblages (Table 8.8). The high degree of spatial variability is generated by spatial differences in the hydrodynamic regime and, therefore, sediment distribution, which in turn is heavily influenced by reef morphology. In turn, as the reef grows, the hydrodynamic and sedimentary regime will change, resulting in temporal as well as spatial differences in key reef processes.

Spatially variable reef accretion rates were used to develop a geometric model of reef growth with depth and time. The geometric model is based on previous conceptual growth models in that it relies on the balance between carbonate production and terrigenous sediment input, but it also integrates key reef processes. The model illustrates how processes vary over space and time but, more importantly, also quantifies these processes with regard to rates of reef accretion (Fig. 8.4). The geometric model for Paluma Shoals was compared with the most recent study of its internal structure and reef accretion history conducted by Palmer *et al.* (2010) using reef cores. The first stage of reef development between 1,000-1,200 yr BP was characterised by a muddy rudstone reef facies and a progressive accumulation of coral colonies stabilised by sediment infilling, and correlates with the first reef growth phase in the geometric model (ClD, import/production dominated; Fig. 8.4). Post 1,000 yr BP, the reef cores indicate that there was a rapid growth phase due to the accumulation of sandy mixed coral floatstone and rudstone (ElD, production/import dominated), followed by a fall in reef accretion rates but an increase in carbonate content within the reef matrix (DWWd, low production). This was interpreted to be an indication of an established coral community. The final stages of reef development based on core analysis indicate that at ~ 250 yr BP, the reef started to laterally prograde towards the shore and by ~100 yr BP a reef flat was established. The geometric model also suggests lateral progradation leewards ~200 yr BP resulting in the development of the wide reef flat (Fig. 8.4). In summary, the geometric model has a number of parallels with the reef accretion history interpreted from reef cores, and illustrates that a comprehensive analysis of carbonate budgets and sediment dynamics can provide accurate insights into reef development.

The development of a geometric model of reef growth for Middle Reef was difficult because of its complex geomorphology. Middle Reef is a linear current-aligned structure consisting of four main reef patches with established reef flats, separated by deeper channels, whereas Paluma Shoals has a comparatively simple morphological structure characterised by an expansive reef flat, an exposed windward edge and protected leeward edge. Reef growth at Middle Reef may have consisted initially of four separate reefs which have since coalesced as they approached sea level, and consequently reef growth is not solely reliant on depth and windward to leeward hydrodynamic gradients due to the interplay between the four reef structures. Nevertheless, the geometric model developed suggests that Middle Reef is younger than Paluma Shoals, but has rapidly accreted reaching sea level ~125 yr BP, although it is likely to have been spatially variable. The dominant processes at Middle Reef were classified as either production-dominated along the windward edge where contemporary coral cover was high, import-dominated within the central zones where sediments accumulated, or export-dominated along the leeward edge where contemporary sediment dynamics suggests sediment removal. However, given that coral cover is high (>30%) in seven out of ten zones, production is the dominant reef process.

8.5.5 Implications for reef health and stability

Projections of future reef ecosystem states typically predict that reefs exposed to increased anthropogenic pressure and global changes in the marine environment (e.g. SST and ocean acidification; Kleypas *et al.*, 2001), will have lower reef accretion potentials and increased rates of reef framework destruction (Hoegh-Guldberg *et al.*, 2007; Veron *et al.*, 2009). Inshore turbid zone reefs are considered to be most at risk from anthropogenic pressures such as reduced water quality (Fabricius *et al.*, 2005; De'ath and Fabricius, 2010), and, as such, they are often perceived to be vulnerable to future environmental change (Fabricius *et al.*, 2007). However, there is growing evidence that many inshore turbid zone reefs, including Middle Reef and Paluma Shoals, are ecologically healthy reflected in high coral cover despite high sediment loads and anthropogenic pressures (Veron, 1995; Ayling & Ayling, 1999a; Smithers and Larcombe, 2003), and, therefore, may not be as vulnerable as previously anticipated. Furthermore, coral communities are composed of corals which are able to persist in an active terrigenous sedimentary regime due to coral adaptations (Anthony, 2006). These adaptations may also provide an increased resilience to extrinsic disturbance events, such as coral bleaching, which threaten reef health and ecosystem stability on clear-water reefs (Anthony & Connolly, 2007).

For inshore turbid reefs situated in shallow waters, reef age and evolutionary state, as well as contemporary ecological status, are important factors to consider when determining reef health and stability (Buddemeier & Hopley, 1988; Hopley *et al.*, 2007). Evolutionary state is partly related to reef structure and partly to available accommodation space and sea level which defines on-going reef accretion potential regardless of ecological status. A reef which has reached sea level experiences a rapid transition from reef growth to reef senility, often termed reef ‘turn-off’, due to the lack of accommodation space (Buddemeier & Hopley, 1988). Therefore, a reef’s accretionary potential may be low even if coral cover is high, and in such cases reef health assessments based purely on benthic cover may deem the reef as healthy and stable, when in fact the reef may be entering into a reef ‘turn-off’ phase. Under present sea level conditions, the ultimate fate of reefs at or close to sea level will be reduced carbonate accretion and reef growth (Smithers *et al.*, 2006; Hopley *et al.*, 2007; Perry & Smithers, 2010; Perry & Smithers, 2011). Parts of Middle Reef and Paluma Shoals are presently at sea level and although considered as ecologically healthy, may potentially be undergoing a transition from reef growth to reef senility. However if sea-level rises, which is typically estimated to rise in the order of 0.5 to 1 m by 2100, Middle Reef and Paluma Shoals will continue to rapidly vertically accrete, given all other environmental conditions are not limiting.

8.6 Conclusions

This study represents the first carbonate budget study for the GBR and focuses on inshore turbid reefs which are considered to be threatened by local and global environmental pressures. Unlike previous assessments of inshore turbid reefs on the GBR, the carbonate budget approach has provided a comprehensive overview of ecological state with rates of carbonate production and destruction. Evaluating rates of carbonate production and destruction provides data on reef responses and processes over time which enables a more accurate assessment of reef health and growth. The carbonate budget assessment for Middle Reef and Paluma Shoals indicates that these two inshore turbid reefs subjected to high sediment loads, periodic flood plumes and strong wind events (e.g. cyclones), are characterised by high gross carbonate production largely due to fast-growing corals, and low carbonate destruction by borers. As such, Middle Reef and Paluma Shoals are ecologically healthy and actively accreting.

Terrigenous sediments are regarded as an important influence on inshore turbid reef growth, but had not previously been quantitatively assessed. This study represents the first quantitative assessment of sediment inputs, transport, storage and removal, using sediment trays, to create a sediment dynamics model. The sediment dynamic model provides a number of insights into sediment movements and associated masses within turbid zone reefs, where the interplay between sediment deposition and resuspension shape benthic community composition and distribution. At Middle Reef and Paluma Shoals, the total annual volume of sediment inputs was high, although only a small proportion (<19%) of imported sediments remained on the reef. The model demonstrates that sediment transport processes are the key to maintaining low sedimentation rates in regions of high sediment yields. The sediment dynamic models may also be used to assess temporal changes to the sedimentary regime, and determine how this may influence contemporary reef health and growth.

Carbonate and terrigenous sediments inputs were used to develop a reef growth model with time and depth. The reef growth model illustrates how the rate and mode of reef growth will vary spatially due to morphological influences, and temporally as a reef approaches sea level. The model incorporates reef age and evolutionary state, and can be used to assess reef growth under changing environmental conditions such as increasing sea level and sediment delivery rates. The model also demonstrates that Middle Reef and Paluma Shoals are still actively accreting, although parts of the reefs have reached sea level and may, in the very near future, ‘turn-off’ despite high coral cover and carbonate productivity. Carbonate budgets and reef growth models that integrate sediment dynamics, therefore, provide a quantitative assessment of turbid zone reef health and growth.

9. CONCLUSIONS

The overall aim of this research was to provide a comprehensive assessment of carbonate and terrigenous sediment regimes for inshore turbid reefs on the central GBR by quantifying carbonate production and destruction together with sediment deposition, resuspension and transport across the reef. Carbonate and sedimentary regime data were used to develop a reef growth model with depth and time which quantitatively linked sedimentary processes to ecological processes. This model is a schematic illustration of how reefs subjected to high terrigenous sediment loads have initiated, grown and developed within marginal environmental conditions and furthers our understanding of how sediments influence ecological through to geological processes. The research had six objectives which are outlined below together with key conclusions:

1) To examine benthic community composition and distribution (Chapter 3 and 4).

- Coral cover was high (>30%) and diversity was moderate to high (>50 species).
- Coral communities were dominated by fast-growing species such as *Acropora* and *Montipora*, sediment tolerant species such as *Turbinaria*, *Galaxea* and *Goniopora*, and coral species tolerant of exposure at low tide such as *Goniastrea*.
- Coral communities were heterogeneously distributed, driven by spatial variations in sedimentation rates and turbidity, which were in turn influenced by wave interactions with reef morphology.
- Temporal community dynamics at Middle Reef demonstrate that coral communities on inshore are robust and resilient.

2) To examine spatial variations in sediment texture and composition (Chapter 4)

- Wave exposure and reef morphology were key drivers of sediment distribution and resuspension over both reefs.
- The mean sediment composition at both reefs reflected mean benthic cover, indicating that carbonate sediments reflect reef carbonate productivity despite

high terrigenous sediment loads. Consequently, well preserved carbonate sediments in the fossil record could provide a temporal assessment of benthic productivity.

- Sediment carbonate composition was related to benthic cover at Middle Reef but not Paluma Shoals due to higher wave energy and sediment redistribution.
- Sediment facies composition (and distribution) was comparable between Middle Reef and Paluma Shoals which suggests that these sediments provide a reef signature for inshore turbid reefs on the central GBR.

3) To investigate the influence of spatial and temporal variations in turbidity on benthic cover (Chapter 5);

- Coral communities on inshore turbid reefs are regularly exposed to large fluctuations in turbidity (>20 NTU), but these events are short-lived, with peak turbidity lasting 3-4 hrs and returning to <5 NTU within 12 hrs.
- Locally driven wind-waves were the key driver of turbidity, but the strength of the relationship between wind and turbidity was dependent on wave exposure.
- Turbidity varied over the reef and was reflected in the community assemblage distribution with a high abundance of heterotrophic corals (e.g. *Goniopora*) in reef habitats subjected to large fluctuations in turbidity (>50 NTU).
- A turbidity model using local wind speed data explained <77% and <56% of the variance in turbidity at Paluma Shoals and Middle Reef, respectively. The model was able to predict naturally high turbidity events and can, therefore, be used by future researchers to determine if the frequency and severity of turbidity events is rising due to increased sediment delivery to inshore regions of the GBR.

4) To quantify the sedimentary regime and examine its role in reef growth (Chapter 6)

- Sediment deposition rates on Middle Reef and Paluma Shoals were lower than previously reported for inshore turbid reefs on the GBR (<122 $g/m^2/day$) as sediment trays measure net as opposed to gross sedimentation rates reported using sediment traps.

- Shorter-term seasonal resuspension rates and net deposition (1-122 g/m^2/day) varied across Middle Reef and Paluma Shoals reflecting spatial differences in sediment composition and hydrodynamics from the windward to leeward edge.

- The total mass of mobile sediments, measured as the sediment flux rate, was high and ranged from 35 g/m^2/day in protected reef habitats to >640 g/m^2/day on exposed reef regions.

- These data demonstrate that despite high sediment delivery rates, sedimentation is low and potentially less of a threat to benthic communities on turbid reefs than previously assumed.

5) To investigate spatial and temporal variations in coral growth and carbonate production (Chapter 7)

- Coral growth rates were comparable to those measured on offshore clear-water reefs and suggest that despite local anthropogenic pressures and global climate change, Middle Reef has a robust and resilient coral community.

- Coral growth was found to vary between reef habitats (windward, inner, leeward edge) due to spatial differences in water motion and sediment dynamics, with highest growth occurring on the windward reef edge for all three coral species measured.

- Lower calcification rates (*Acropora* and *Turbinaria*) in summer when SSTs (monthly average 29 ^{o}C) and rainfall (monthly total >500 mm) were high indicate that corals maybe 'stressed' and potentially less resilient to anthropogenic pressures when they are exposed to multiple natural pressures.

6) To quantify carbonate production and destruction together with sediment import, storage and export (Chapter 8).

- Net carbonate production was high (>6.9 kg/m^2/year) due to high coral cover (>30%), high coral calcification rates (*Acropora* average linear extension rate

6.3 mm/year), and low bioerosion rates (0.3 to 5 kg/m^2/year), but varied spatially with highest net carbonate production (>10 kg/m^2/year) within deep (>-2 m at LAT) windward reef zones.

- High carbonate framework production has enabled Middle Reef and Paluma Shoals to vertically accrete rapidly, reaching sea level in 790 to 1,190 years regardless of high terrigenous sediment inputs and fluctuating turbidity.
- The sediment dynamics model illustrated that >11,000 tonnes are delivered to Middle Reef and Paluma Shoals each year, but over 81% of sediments are removed, with net sediment accumulation limited to sheltered reef habitats.
- The model demonstrates that sediment transport processes are the key to maintaining low sedimentation rates in regions of high sediment yields.
- Spatially variable carbonate production and sediment dynamics were used to develop a reef growth model which illustrated that within terrigenous settings reef growth will vary in the rate and mode of growth with depth, and spatially from the windward to leeward reef edge.
- The model demonstrates that Middle Reef and Paluma Shoals are still actively accreting, although parts of the reefs have reached sea level and may, in the very near future, 'turn-off' despite high coral cover and carbonate productivity.
- These data demonstrate the importance of assessing reef evolutionary state with ecological assessments to evaluate future reef growth under changing environmental conditions. This can be applied to all reef types, but particularly those approaching sea level.

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