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JAMES COOK UNIVERSITY
AUSTRALIA

# Chapter 1. Introduction and Aims

## 1.1. Introduction

Coral reef growth (at least in the popular press) is commonly associated with clear waters, unlimited visibility, and colourful arrays of fish and coral species. This association is often carried into environmental and geological interpretation. However, recent sedimentological studies within the central Great Barrier Reef (GBR) lagoon indicate that coral reef growth is common in turbid, shallow coastal environments, where coral initiation and growth is aided by prevailing hydrodynamic and sedimentological conditions (Woolfe & Larcombe, submitted; Larcombe *et al.*, 1995). These observations contradict the widely published view that sediment-laden water is necessarily detrimental to the health corals (e.g. Pastorock & Bilyard, 1985; Rogers, 1990; Stafford-Smith, 1992).

Paluma Shoals, the primary focus of this study, are a series of near-shore patch reefs located within the inner-shelf terrestrial sediment wedge of southern Halifax Bay, GBR, Australia. The quantity of sediment in suspension within the inner-shelf terrestrial sediment wedge distinguishes these reefs from those of the mid and outer-shelf (Larcombe, 1995). The corals at Paluma Shoals experience water conditions well outside the known "established" tolerance levels for turbidity, and yet are a healthy, thriving population. These "turbid water reefs" are probably common along the inner-shelf of the GBR, the Gulf of Papua and many locations along the West Australian coast (Woolfe & Larcombe, submitted) but their documentation within the literature is scarce. However, examples of fringing reef development in areas of high topographic relief and rainfall are numerous (e.g. Brown *et al.*, 1992; Chansang *et al.*, 1992; Macintyre *et al.*, 1992) and it can thus be inferred that turbid water reefs may be common throughout the tropical latitudes.

Coral reefs such as Paluma Shoals also provide insights into the Holocene evolution of the GBR, because they form a potential analogue to initiating reefs (Larcombe, 1995; Larcombe *et al.*, 1995). The association of coral reefs and turbid water should come as no surprise, because muddy reefal limestones are common in the geological record (Burchette, 1981; Frost, 1981) yet, until recently, nearshore turbid water reefs have remained scientifically neglected. Recent studies indicate that little terrigenous sediment is reaching the outer-shelf reefs on the GBR (Brodie, 1995; Okubo & Woolfe, 1995; Taylor, 1995) and therefore concerns regarding the impacts of potential increased terrigenous sediment accumulation (and turbidity) should be directed towards inner-shelf reefs. The scientific neglect of near-shore coral reefs is unjustified because, close to the coast, they are turbidity and sedimentation regimes. Near-shore turbid water reefs are likely to provide valuable potential insights into the impacts of these processes on all types of reefal communities.

Anthropogenic influences have undoubtedly increased the volume of terrigenous sediment entering the GBR lagoon (Belperio, 1983; Moss *et al.* 1992, Neil & Yu, 1995) and the impacts of increased sediment yield to GBR corals are widely inferred (Buddermeier, 1992; Brodie & Wachenfield, 1995). However, baseline data are not yet established, including quantification of increased terrigenous sediment flux to the GBR lagoon (Larcombe *et al.*, 1996) and the threshold tolerance levels of coral reef organisms to factors such as turbidity and sediment accumulation rates (Rogers, 1990).

Establishment of the responses of coral reef organisms to natural and anthropogenic increases in sediment accumulation and turbidity, is an essential prerequisite to successful management of the GBR (Stafford-Smith, 1992). Investigations regarding the impact of sediment accumulation and turbidity on corals relate mostly to post-mortem studies, rather than the effects of sub-lethal or long-term effects of sediment stress (Hubbard, 1988). The present data cannot indicate whether GBR corals are well within their tolerance limits, or if slight increases in turbidity and sediment accumulation rates will expose corals to acute or chronic stress (Johnson & Carter, 1987). Stafford-Smith (1992) notes that the local and regional sedimentary and turbidity regimes may be an important control on the ecological distribution of coral species. Woolfe & Larcombe (submitted) suggest that regional and local hydrodynamics control many of the factors which affect coral reef growth, including turbidity and sediment accumulation. Therefore, to establish baseline data of organism responses to sedimentation and turbidity it is essential to gain an understanding of the factors which control water quality.

To gain a full understanding of the controls upon water quality at coral reefs, regional and local sedimentary, turbidity and hydrodynamic conditions need to be assessed. These conditions from Paluma Shoals are compared to Phillips Reef located approximately 13 km north of Paluma Shoals (Figure 2.2).The collection of high-frequency, high-quality turbidity and hydrodynamic time-series data is now possible with the advent of self-cleaning optical backscatter technology (Kineke & Steinberg, 1992; Ridd & Larcombe, 1994). This technology allows the collection of continuous high resolution, turbidity and hydrodynamic data for periods of up to one month (e.g. Larcombe *et al.*, 1995a).

By understanding the hydrodynamic, sediment dynamic and water quality regimes at coral reefs, geologists gain valuable insights into factors which control coral reef growth and distribution. However, without consultation between physical and biological scientists the successful application of this data cannot reach its full potential.

### 1.2. Aims

- To examine, identify and compare the turbidity regimes and the hydrodynamic processes at Paluma Shoals and Phillips Reef.
- To examine, identify and compare the sediment distribution patterns adjacent to Paluma Shoals and Phillips Reef.
- To identify the potential causes of differences in turbidity values (NTU) between Paluma Shoals and Phillips Reef.

# Chapter 2. Regional Setting

## 2.1 The Great Barrier Reef

The Great Barrier Reef (GBR) extends through 15 degrees of latitude north of 24° S, NE Australia, forming the worlds largest marine park. The Great Barrier Reef Marine Park covers an area of 343 800 $km^2$ and is comprised of over 2900 individual fringing, ribbon and barrier reefs (Parnell, 1988). The GBR Marine Park is divided into four sections: the Mackay/Capricorn section (148 800 $km^2$) the central section (77 000 $km^2$) the Cairns section (35 000 $km^2$) and the Far Northern section (148 800 $km^2$). The width of the Great Barrier Reef province varies from 24 km near Cape Melville in the northern region, to 290 km in the southern region at Cape Townsend (Maxwell, 1968). Water depths on the continental shelf generally decrease northward from greater than 55 m in the southern region to 36 m in the northern region (Maxwell, 1968).

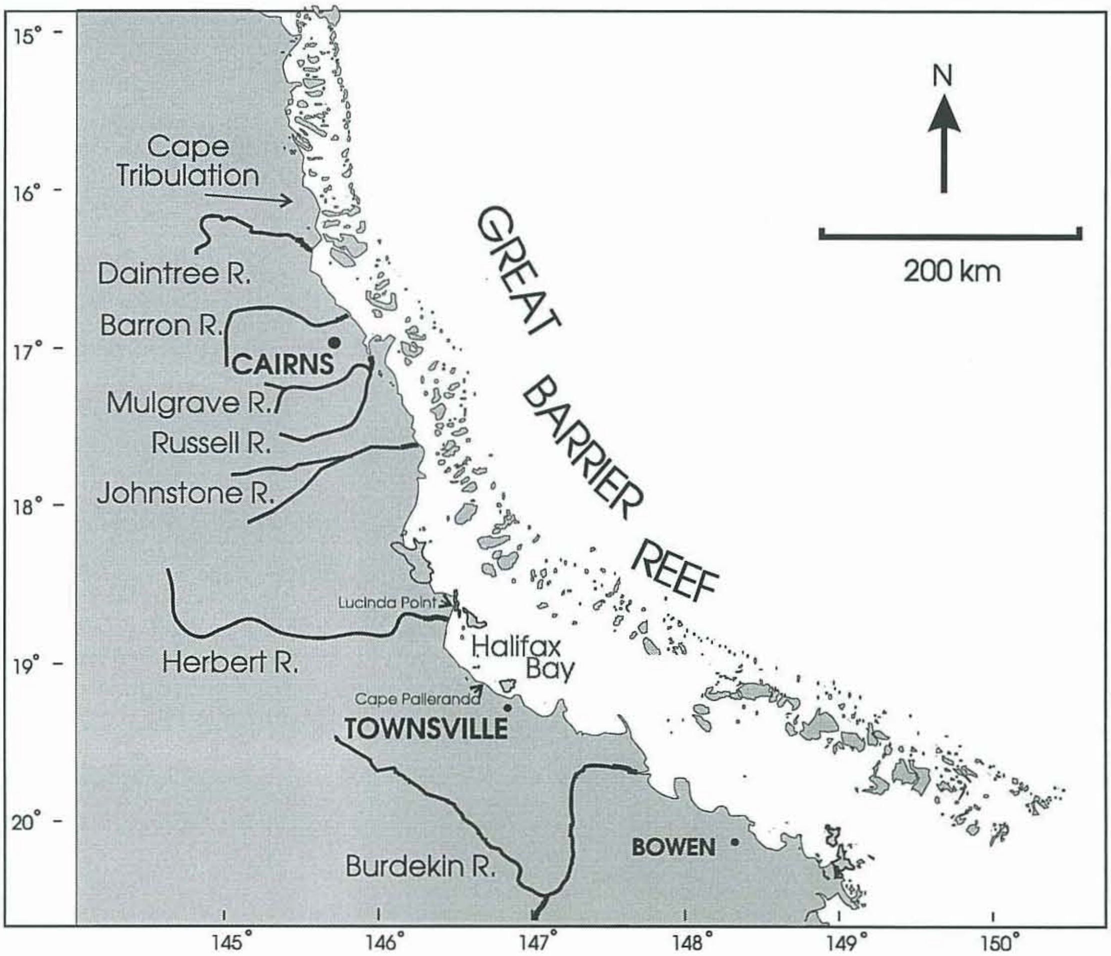


**Figure 2.1.** *Location of Halifax bay and major rivers within the central and northern sections of the GBR. (Map drawn by R..G. Purdon).*

The GBR shelf is divided on the basis of water depth into inner-shelf (0-20 m) mid-shelf (20-40 m) and outer-shelf (40-60 m) zones (Maxwell, 1968; Belperio, 1978). Three distinct regimes of post-glacial sedimentation correspond to these zones (Maxwell, 1968; Belperio, 1978; Belperio, 1983; & Johnson, 1985). These including:

- Modern terrigenous sands and muds of the **inner-shelf**, partitioned into a coastal wedge.

- Terrigenous-starved **mid-shelf**, comprised of reworked terrigenous and modern carbonate sediments (palimpsest) (Johnson & Searle, 1984; Gagan *et al.*, 1990; Carter *et al.*, 1993).

- A carbonate-dominated **outer-shelf** (Maxwell, 1968; Harris et al., 1990).

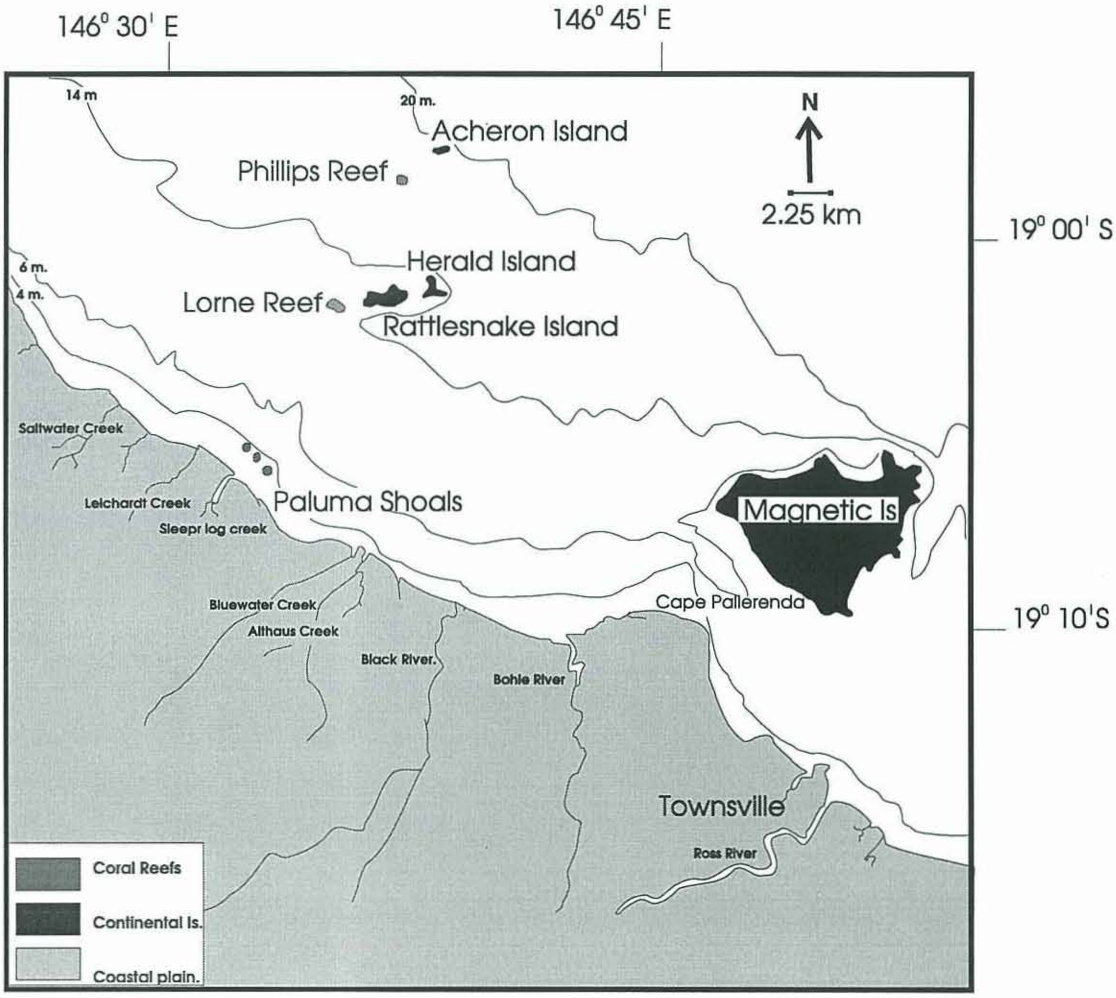


**Figure 2.2.** *Bathymetric map and the location of Paluma Shoals and Phillips Reef.*

## 2.2 Location of Study Site

Paluma Shoals ($19^0$ 05 43′S-$146^0$ 33.5′E) and Phillips Reef ($18^0$ 59.30′S-$146^0$ 37.04′E) are located at the southern end of Halifax Bay (Fig. 2.2). Halifax Bay is a 100 km long semi-protected embayment, stretching from Cape Pallerenda northwards to Lucinda Point (Figure 2.1).

Paluma Shoals are a series of near-shore patch reefs located in ca. 2.5-6 m of water, ca., 1-5 km offshore. Phillips Reef is situated approximately 13 km north of Paluma Shoals at a depth of 16 m. Herald, Rattlesnake and Acheron islands are situated approximately 9 km from the coastline. Sleeper Log, Two Mile and Liechhardt creeks debouche onto the inner shelf, draining the adjacent escarpment and coastal plain adjacent to Paluma Shoals.

The coastal plain varies in width from 5 km north of Paluma Shoals, to 84 km in the vicinity of Home Hill (Hopley and Murtha, 1975). A mosaic of erosional debris and alluvial deposits including slope talus, outwash alluvial fans, flood plain alluvium and weathered regolith, blankets the coastal plain.

## 2.3. Bathymetry

The continental shelf is divided on the basis of water depth into inner (0-20 m) mid (20-40 m) and outer (40-60 m) shelf zones (Belperio, 1978). Searle *et al.*, (1978) suggests that the change in shelf gradient at the 20 isobath is related to the edge of the prograding modern terrigenous sediment wedge. Regionally the shelf is relatively flat (1.1 m/km) and contains coral reefs and isolated continental islands composed of Permo-Carboniferous granites and volcanics (e.g. Magnetic Island, Rattlesnake Island, Herald Island and Acheron Island) (Johnson and Searle, 1984). Most of Halifax Bay is less than 20 m deep with a gentle seaward slope of the seafloor of approximately 0.79 m/km (Tye, 1992).

## 2.4. Climate

The region experiences a seasonally dry, tropical semi-arid climate. Summer temperatures range from $20^0$-$34^0$C (November -April) and winter temperatures from $11^0$-$29^0$C. The majority of the annual rainfall falls during the summer wet season. The average yearly rainfall for Townsville is 1163 mm but is highly variable. February is the wettest month with a mean rainfall of 319 mm and August is the driest, with a mean of 9 mm (averaged over 100-year period) (Oliver, 1978). Rainfall was minimal during the instrument deployment period (nephelometers & current meters) thus, exchange of water from Bluewater, Sleeper Log and Two Mile creeks was tidally dominated.

Cyclones often affect the north Queensland coast. Ninety-one percent of all cyclones occur in the months of November to March. Most tropical cyclones develop close to the monsoon trough which is often present over the Coral Sea or the Gulf of Carpentaria during the summer months (Wilkie, 1995). Tropical cyclones originate in the inter-tropical convergence zone between $8^0$S and $18^0$S in the Coral Sea, and they often exhibit erratic paths. However, their movement is predominantly in a southwesterly direction, toward the mainland. Cyclones or severe rain depressions can result in storm surges, raising water levels as high as 3 meters and inducing major flood events (Heron *et al.*, 1979). Over the 30 year period between 1940 and 1969, 22 tropical cyclones passed within 167 km of the Townsville region (Oliver, 1978).

Southeasterly trade winds prevail over the GBR shelf for most of the year. Data from a single Townsville wet season indicates that winds blow from the east or southeast for 60% of the time, with wind strengths greater than 7.5 m/s for 25% of the time (Larcombe and Ridd, 1993). Fetches for the major wind directions are:

NW 60 km
N 65 km
NE 60 km
E 120 km

**2.5. Sediment Sources**

Within the GBR, major rivers form point sources of sediment entering the lagoon (Figure. 2.1). Most of the terrigenous sediment enters the GBR lagoon in a few days following intense seasonal rainfall events (Belperio, 1978; Belperio, 1983; Hopley, 1982; Taylor, 1995). These rainfall events are episodic, highly variable and often associated with tropical cyclones. Variation in rainfall is the most significant control on temporal variation in sediment yield, influencing ground cover, runoff volume, slope stability and available energy for sediment detachment and transport (Neil, 1995).

Initial assessments of fine-grained and coarse-grained sediment entering the GBR lagoon were compiled by Belperio (1978) revised estimates have been produced by Moss (1992) and Neil and Yu (1995). These studies (largely desktop) indicate that most of the sediment entering the lagoon arrives via the Burdekin, Fitzroy and Cape York rivers (Neil & Bofu Yu, 1995; Johnson, 1995) The Burdekin River has a mean annual discharge of approximately 9.8 x $10^6$ litres, concentrated during the wet season (Belperio, 1978). An 'average annual' sediment load of 3.45 x $10^6$ tonnes was computed by Belperio (1978), who has noted that an equivalent load may be discharged in less than 24 hours during major flood events. The Burdekin River, located ~100 km south of Paluma Shoals, is the largest regional source of terrigenous sediment, and may contribute up to 0.4 million tonnes of sediment to Halifax Bay per year (Belperio, 1978; Belperio, 1983; ).

### 2.6. Sediment Partitioning

The shoreward movement of sediment across the inner GBR shelf has been inferred by numerous studies (Belperio, 1983; Gagan, 1990). Most of the sediment is being trapped in the inner-shelf terrigenous sediment wedge, leaving the mid- and outer-shelf zones starved of terrigenous sediment (Carter *et al*, 1993; Okubo & Woolfe, 1995).

Southeasterly trade winds, and the resultant wave and wind driven currents, are a major controlling factor in sediment dispersal on the GBR shelf (Belperio, 1978; Ridd *et al.*, 1995). The southeasterly trade winds generate northward-and shoreward-directed currents. Sediment partitioning across the shelf has also been attributed to episodic events including cyclones. However, the orientation of features such as bars and spits suggest that sedimentary processes along the coast are dominated by the southeasterly trade winds (Woolfe *et al.*, 1995).

The shoreward-directed transport of sediment produces variations in near-bed suspended sediment concentrations (SSC) across the GBR shelf. The magnitude of near-bed SSCs depends upon the availability of sediment suitable for resuspension, the local wave regime and to a lesser extent, tidal amplitude (Larcombe *et al.*, 1995a). The resuspension of inner-shelf sediment produces a turbid water column which is trapped within the coastal boundary layer (Larcombe *et al.*, 1995a)

### 2.7. Oceanography

The difference in average daily sea temperature between sites separated by a few hundred metres to a few kilometres is generally less than 0.1$^0$C (Berkelmans, 1995). However, between Magnetic and Orpheus islands, separated by a distance of 75 km, average sea temperatures differ by 1 and 2$^0$C (Figure 2.3) The average daily sea-surface temperatures for Magnetic Island for July and January are 21.95$^0$C and 31.90$^0$C respectively. Orpheus Island experiences average daily sea temperatures of 22.20$^0$C for July and 30.10$^0$C for

January (Berklemans, 1995). Therefore, average daily sea temperatures for Paluma Shoals and Phillips Reef probably fall between those of Magnetic and Orpheus islands.

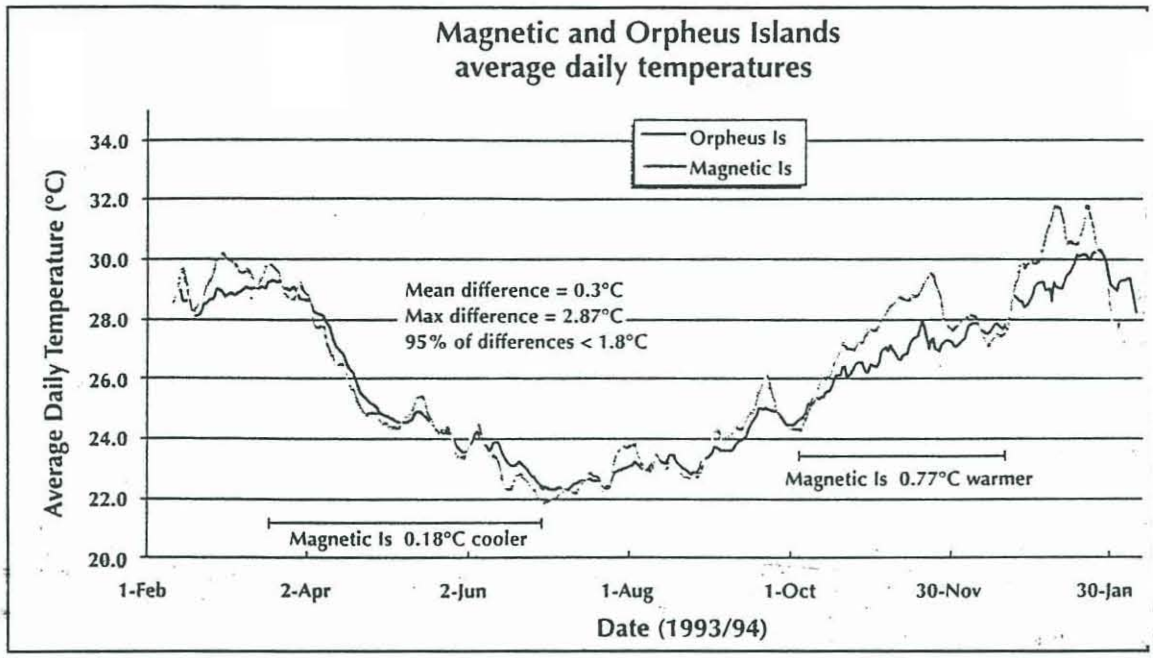


**Figure 2.3.** *Variation in sea surface temperature at Magnetic and Orpheus islands (from Berklemans, 1995).*

Pickard *et al.* (1977) show that salinity variations within the GBR lagoon are related to freshwater runoff from the mainland. Low salinities correlate with summer rainfall, and high salinities with dry periods. The water column within the GBR lagoon is well-mixed for most the year, but some stratification may be associated with summer freshwater influxes (Pickard *et al.*, 1977). Data from Cleveland Bay indicates that salinity varies between 27 and 35 with extreme variations due to cyclonic rainfall, reducing salinity over reef flats to less than 20 (Johnson, 1985).

The tide cycle at the Townsville Harbour (the nearest standard port for tide level predictions) is primarily semi-diurnal with a diurnal inequality (Ridd *et al.*, 1995) and a maximum range at spring tides of 3.8m. Large spring tides flood the coast between January and July with one major flood per day, followed by a smaller ebb fall an even smaller flood and then a moderate ebb (Figure 2.4) (Ridd *et al.*, 1995). These flood dominated tidal currents may direct bedload transport onshore (Bryce, 1995; Larcombe & Ridd, 1996). Ridd et al. (1995) notes that for the majority of the GBR shelf, ebb tides are probably insufficient to move sediment.

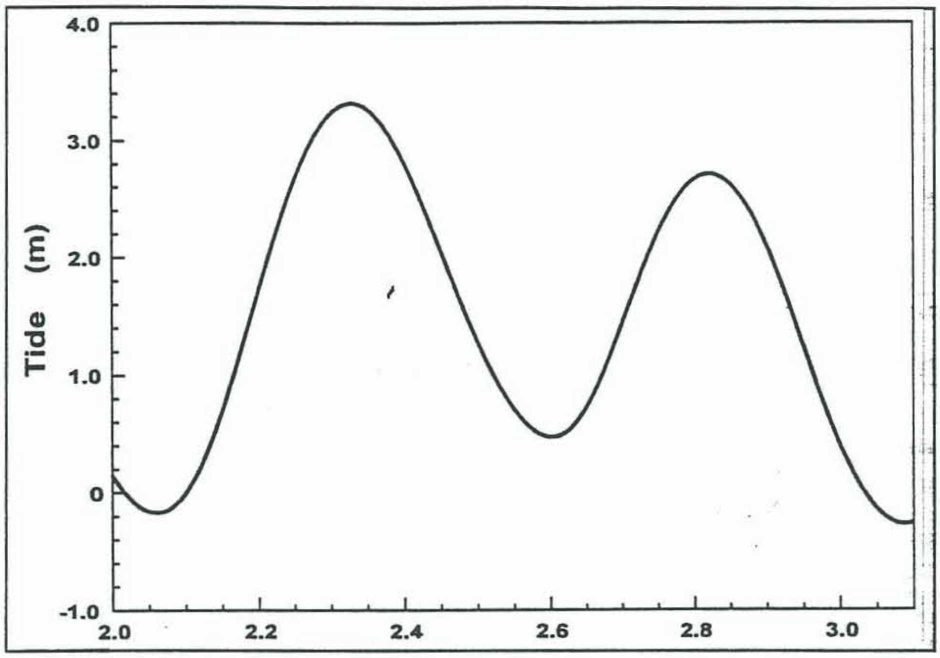


**Figure 2.4.** *Typical tidal curve (X - axis weeks) for a spring tide from the GBR shelf (from Ridd et al., 1995).*

# Chapter 3. Materials and Methods

### 3.1 Seismic Survey

The 18 m research vessel *RV James Kirby* (Cruise No.KG954 leg-1) was equipped with a 3.5 kHz ORE precision depth recorder (PDR) to obtain high resolution images of the surface and shallow subsurface features of Halifax Bay. This data was required to determine the thickness and lateral extent of surfical sediments. The profiles from the PDR were printed on a dual channel, EPC 3200 paper recorder. The system was operated in calm seas and at an average ship speed of 6 knots (~11 km/hr). The PDR was triggered every 0.25 seconds at an energy level of 10 kW providing a sub-bottom penetration of 10-15 m. The position of KG954 survey lines, seismic stations and way points are listed in Appendix 3.1 and plotted on figures 3.1 and 5.1. Bed elevation data has been adjusted to the position of Australian Height Datum (AHD). Water depths and bed elevation data for the seismic profiles are tabulated in Appendix 4.1. Stratigraphical interpretation of the seismic records were calculated assuming a velocity of 1500 m/s in the water column and 2000 m/s for the sediments.

### 3.2 Vibrocore recovery and analysis

Core sites (Figure 3.1) were selected to coincide with seismic lines, to provide ground truthing of the seismic profiles. Coring was undertaken using a 76 mm-diameter aluminum core barrel within a stern-mounted, 5 m frame-supported vibrocorer. In total, 7 cores (KG954-VC1 to KG954-VC6) were collected on cruise KG954 leg-3 by R.G. Purdon.

Laboratory analysis of the vibrocores involved splitting, visual logging and photography (colour and monochrome). Subsamples were taken at ca. 50 cm intervals from one half of the core. The remaining half of the vibrocore was labelled, wrapped in protective plastic and stored for future reference. Analytical methods and results for the vibrocore data including grain size, textural and mineralogical analysis are listed below.

### 3.3 Sediment sampling

Surficial sediment samples were collected from 135 sites. Fourty-one samples were collected by hand from the surrounding beaches, creeks and mangrove swamps, aerial photographs and a hand-held Magellan GPS were used for location (Figure 6.1). Nine samples were taken from the tidal creek beds (Sleeper Log and Two Mile creeks) using a small hand-held Van-Veen grab sampler. Twenty-seven surficial reef samples from Paluma Shoals were collected by hand, scuba diving and snorkelling from an inflatable dinghy.

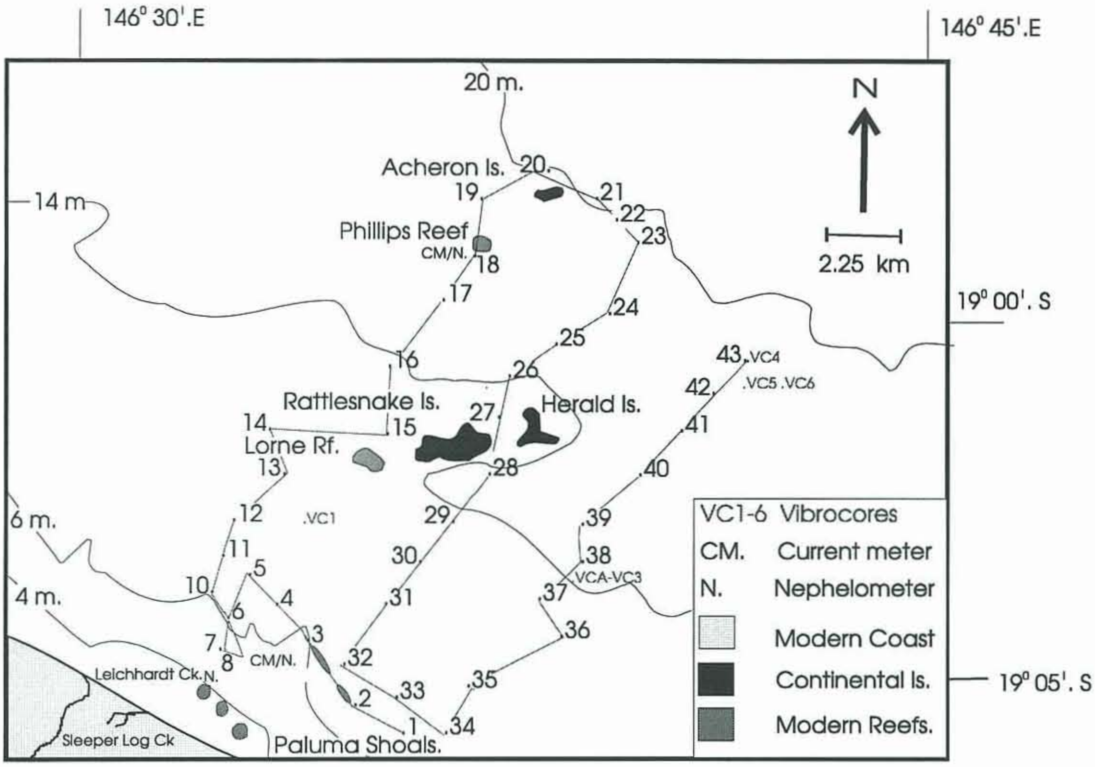


**Figure 3.1.** *Positions of seismic lines, seismic stations, vibrocores, current meters and nephelometers.*

The research vessel *RV James Kirby* (Cruise KG954 leg -1) was used between the 5-9-95 and the 7-9-95 to collect fifty-eight offshore sediment samples (Figure 3.3. and Appendix 3.1). The collection of these samples, KG954G1-KG954G58 was undertaken using a large frame-mounted Van-Veen grab.

### 3.4 Grain Size Analysis

Analysis was determined for 32 size classes over a closed range of 4-2000 microns using a Malvern Mastersizer-X particle sizer. Samples were removed from bulk samples, wet sieved through a 1 mm mesh, dispersed in water and subjected to ultrasound for 15 seconds. The resultant data represent 15,000 laser observations of each sample. This method allows rapid, accurate and reproducible measurement of grain size distributions.

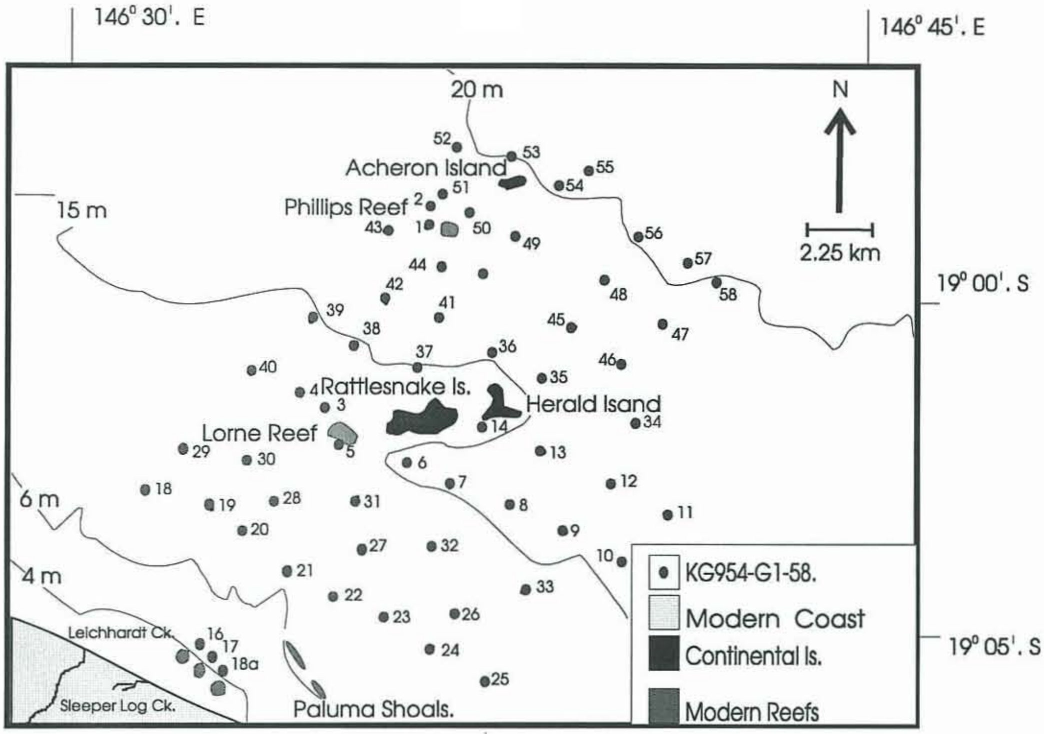


**Figure 3.3.** *Positions of surficial sediment samples KG954-G1 to KG954-G58. For sample latitude and longitude see Appendix 3.1.*

The grain size fractions between 1mm and 2 mm and >2 mm, were sieved, dried and weighed (Appendix 6.1). These data were combined the <1 mm fraction which had been analysed using the particle sizer and exported to Exel 5.0 using a modified version of Woolfe and Michibayashi's (1995) dynamic exchange (DDE) link. The resultant data set was blended and statistically grouped using Entropy 4.2 (Woolfe & Michibayashi, 1995) a Quick BASIC program derived from Semple *et al.* (1972) multivariant extension to information theory .

The resultant entropy groups were determined by a compromise between achieving a high Rs statistic (Semple *et al.*, 1972) and empirical observation (Woolfe, 1995). For this data set, the statistical optimum number of groups was determined by measuring the point at which the Rs statistic no longer increases significantly with the addition of an extra group. Seven entropy groups were chosen as the optimum number for this data set (Figure 6.25 & Appendix 6.3).

### 3.5 $CaCO_3$ Determination

Carbonate dissolution was performed on all samples to determine the weight percent of $CaCO_3$. Sediment samples were placed in pre-weighed pyrex containers and dried at $110^0$ C, and reweighed. Dissolution of the carbonate fraction was achieved by saturation of the sample in 10% $HN0_3$ and frequent agitation. These steps were repeated until complete dissolution of the carbonate was observed. The samples were washed with water, decanted to remove acid residue, oven dried and reweighed. Results are given in Appendix 6.2 and Figure 6.15.

### 3.6. Optical Mineralogy and Textural Examination of Surface and Vibrocore sediments

Textural and mineralogical examinations were performed on 135 samples. A Nikon 102 binocular microscope was used to detail hand specimen textural and mineralogical characteristics. Visual grain size estimations are based on the Udden-Wentworth classification scheme (Figure 3.4) and roundness and sphericity classes after Powers (1953) and Shepard (1963).

### 3.7. XRD Analysis

Whole sample XRD analysis were undertaken using a Siemens D5000 X-ray diffractometer utilising Cu K-alpha radiation at 2-theta angles of between $1^0$ and $65^0$. Sediment samples (Table 6.3) were selected for XRD analysis to determine the XRD-peak ratios of kaolinite:illite:smectite (K:I:S) to establish the dominant clay mineralogy of the sediments and infer a possible source of the clays to Paluma Shoals.

### 3.8 Water Turbidity

Water turbidity data were collected by three self-cleaning optical backscatter nephelometers. These were mounted to an anchored frame and deployed for 1410 hours (35 days) between 6/9/95 and 9/10/95 (Julian days 247-284) Their sensors pointed horizontally at 0.3 m above the sea-bed (Table 3.1 & Appendix 3.1). The instruments recorded mean turbidity every 5 minutes (averaged over 10 seconds). At Paluma Shoals and Phillips Reef the nephelometers were deployed on coarse grained coraline sediments. One of the nephelometers deployed at Paluma Shoals was not recovered.

Nephelometers are optical backscatter devices (OBS), which emit light (usually infra-red) into a fluid suspension and measure the light reflected back to the transducer from the particles in suspension (Larcombe, *et al.*, 1995). The light signal is converted into a voltage by the transducer, then stored into a data logger.

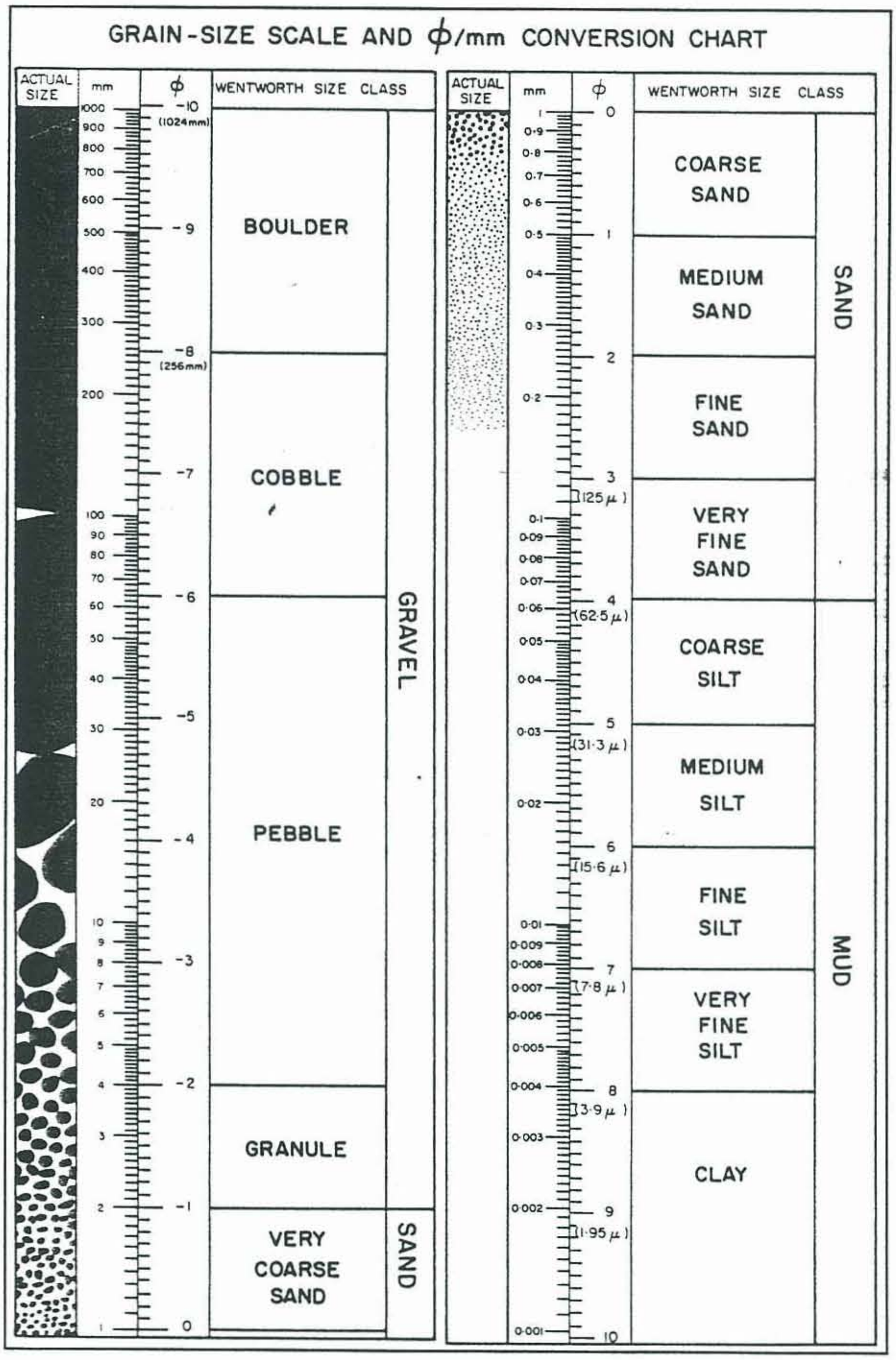


**Figure 3.4.** *The Udden-Wentworth grain size classification chart (from Lewis & McConchie, 1993).*

To correct for the offset voltage of each nephelometer and the relationship of voltage to SSC, calibration is required. The output of optical backscatter nephelometers is dependent upon the nature and the grain size distribution of sediment in suspension (Gibbs & Wolanski, 1992; Green & Boon, 1993) therefore, calibration of field data is necessary.

| Site | Instrument | Latitude | Longitude | Water depth | Period of deployment |
|---|---|---|---|---|---|
| Paluma Shoals | Current meter-1<br>Nephelometer-4 | $19^0$ 05.43′S | $146^0$ 33.51′E | 4.9 m | 6/9/95<br>to 3/10/95<br>(671 hours) |
| Paluma Shoals | Nephelometer-1 | $19^0$ 05.53′S | $146^0$ 33.26′E | 4.0 m | 6/9/95 3/10/95<br>(698 hours- instrument lost no data) |
| Phillips Reef | Current meter-2<br>Nephelometer 4 | $18^0$ 59.30′ S | $146^0$ 37.04′ E | 16.0 m | 5/9/95-3/10/95<br>(669 hours) |

**Table 3.1** *Current meter and nephelometer deployment details.*

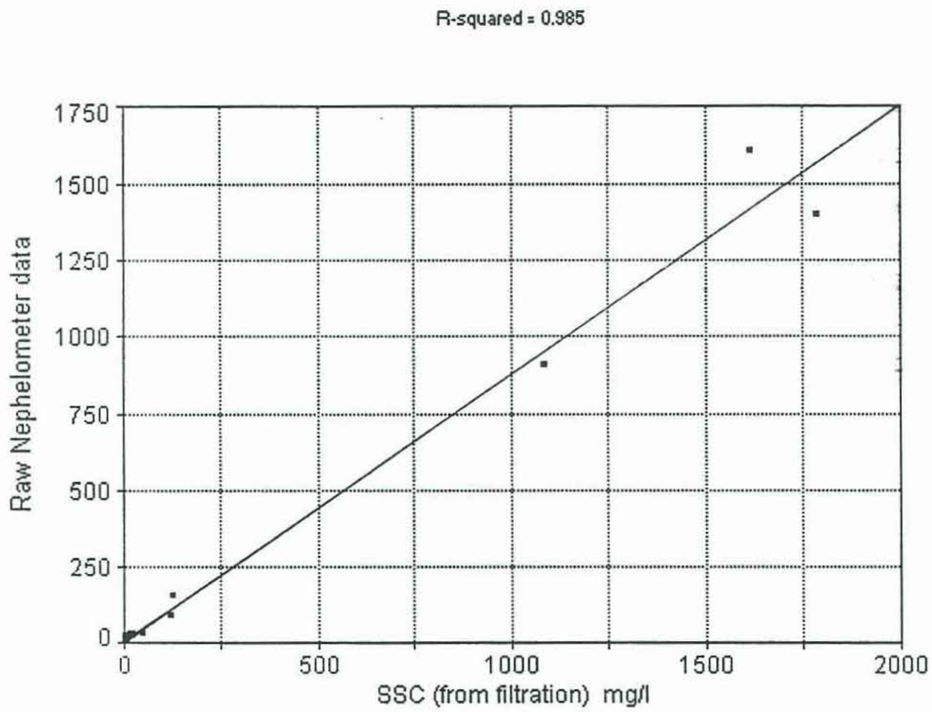


**Figure 3.5.** *Calibration curve between raw nephelometer output and SSC as determined by filtration of water samples (From Larcombe et al., 1995).*

Larcombe *et al.* (1995) state that the calibration scatter is the predominant source of uncertainty in the presented SSC values. Employing a linear fit, their is a 95% chance that individual readings obtained from nephelometers will indicate the true SSC to within ca.±30% (Figure 3.5). Larcombe *et al.* (1995) note that the instrument precision is better than 2%, with calibration differences between individual nephelometers, negligible. For this study turbidity levels are given in nephelometic units (NTU) and not converted to SSC values.

### 3.9. Hydrodynamic Data

Tidal height, wave height, wave direction, current speed and current direction data were collected using two Woods Hole SP2100 current meter/wave gauges (1 each at Paluma Shoals & Phillips Reef. The instruments were mounted to the same anchored frame that housed the nephelometers, which were positioned 0.3 m from the sea-bed (Figure 3.1 and Table 3.1). These data were collected in 1995 from Paluma Shoals between Julian days 249.31 to 276.48 (671 hours) and Phillips Reef between Julian days 248.54 to 276.42 (669.5 hours).

There are three wave fields identified within the data. The wave spectra are divided into local wind-waves (with wave periods < 5 seconds) transitional waves (with wave periods between 5-6 seconds and swell waves (with wave periods > 6 seconds). Wave heights are expressed as the significant height of the wave spectrum ($H_{sig}$) defined as $2\sqrt{2}$ times the root mean square of the wave amplitude which equates to the approximate equivalent mean height of the highest third of the waves (Larcombe *et al.*, 1995). Wave and current direction are given in degrees and current velocity in cm/s.

### 3.10. Meteorological data.

To complement the hydrodynamic data, wind directional data for the instrument deployment period was obtained. Wind data were recorded at 3-hourly intervals (averaged) at Townsville Airport 25 km south of Paluma Shoals (data provided by the Townsville Bureau of Meteorology). Wind direction is in "true" degrees and wind speed is in m/s.

### 3.11 Coral Taxonomy

Taxonomic data was recorded from Paluma Shoals by Stuart Watson, from the Marine Biology Department, James Cook University. Data was collected on the 1/12/95. Coral cover was assessed using line intercept transects, this method involved SCUBA diving and identifying and assessing the coral and coral cover (percent) underneath a 10 m length of tape (Figure 3.6) The line intercept transect method allows the results of this dataset to be compared with other studies of near-shore reefs. Ten 10 m transects were completed (Figure 4.1) on the leeward reef flat and a further 10 on the windward reef flat.

The linear intercept distances (distance between taxon along tape) of each taxon were converted into a proportion of space occupied along the 10 m transect; giving percent coral cover estimates (figures 4.1 & 4.2) (Watson, 1996). Using the same linear sampling technique, the presence of juveniles were recorded. This method is more suited to percent cover estimates rather than the number of colonies. However, data is presented in Table 4.3 which relate to the abundance of juveniles along the 100 m transect at each site. Juveniles are defined as colonies less than 5 cm in diameter (Bak and Engal, 1979; Watson,1995).

**Figure 3.6.** *Collection of coral cover and juvenile percent data using the line intercept transect method. Data is collected from coral colonies (family Favidae) intercepted by the tape.*

# Chapter 4. Reef Morphology and Coral Taxonomy of Paluma Shoals and Phillips Reef.

## 4.1. Introduction

Water clarity and sediment supply are widely inferred to be important factors influencing the establishment of coral reefs (Pastorock & Bilyard, 1985; Cortes & Risk, 1985; Rogers, 1990; Stafford-Smith, 1992). The variations in sedimentary and turbidity regimes may also be important factors influencing the ecological distribution of coral species (Hubbard, 1986; Macintyre *et al.*, 1993; Stafford-Smith, 1992). Regional and local hydrodynamics control many of the factors which affect coral reef growth, including turbidity and sediment accumulation (Woolfe & Larcombe, submitted). Terrigenous influx or resuspension of bottom sediments via wind or swell-waves can produce high concentrations of suspended sediment (SSC), and turbidity on the inner-shelf of the GBR (Larcombe *et al*,. 1995). Turbidity causes light attenuation and can alter the intensity of light which reaches reef organisms (Hopley & van Woesik, 1988) and it is well documented that turbidity and accumulation of sediment may have detrimental affects to coral reef communities (Pastorock & Bilyard, 1985; Cortes & Risk, 1985; Rogers, 1990; Stafford-Smith, 1992). Numerous experiments have been performed to asses the effects of sedimentation and turbidity on corals (Marshall & Orr, 1931, Hubbard & Pocock, 1972, Rogers, 1979, Pastorock & Bilyard, 1985, Stafford-Smith, 1990) and they have revealed that sedimentation and turbidity has effects at the organism level. These include (Bak, 1978):

- Suspended sediment depresses light levels, lowering symbiotic algal activity and hence calcification rates;
- Sediment blankets cause coral suffocation;
- The energy used in sediment removal saps polyp vitality;
- Suspended sediment has unfavorable effects on plankton food sources;
- Suspended sediment and soft sediment cover of substrates prevents successful settlement of planuae;
- Freshwater associated with riverine sediment flux can cause osmotic problems for coral polyps.

The responses of coral communities that experience high sedimentation and turbidity may include (Rogers, 1990):

- Decreased species diversity with some species absent;

- Reduced live coral coverage;
- A greater abundance of forms and species adapted to sediment smothering or reduced light levels;
- Reduction in the average size of coral colonies because of their greater efficiency at rejecting sediments;
- Lower growth rates;
- An upward shift in depth zonation;
- An increase in branching forms.

The corals at Paluma Shoals experience water conditions outside the known published tolerance levels for turbidity, with coral growth aided by prevailing hydrodynamic and sedimentological conditions (Woolfe & Larcombe, submitted; Larcombe *et al.*, 1995a; Chapter 7). These observations contradict the widely published belief that sediment-laden water is necessarily detrimental to the health coral reef organisms. To establish the effects of the turbidity levels at Paluma Shoals an evaluation of the coral community is required. This chapter provides a general overview of the reef morphology of Paluma Shoals and Phillips Reef, and presents the results of a biological survey (Watson, 1996) of the coral community from both Paluma Shoals and Phillips Reef.

**4.2. Reef Morphology 1. Paluma Shoals**

Paluma Shoals are a series of nearshore reefs located within the inner-shelf terrestrial sediment wedge of southern Halifax Bay. SCUBA, aerial photography and seismic profiles have revealed the existence of five individual reefs in the nearshore zone of southern Halifax Bay. Of the five reefs, two have been investigated in detail and are annoted the northern reef (N) and the southern reef (S) for convenience (Figure 4.1). These two reefs are located in ca. 2.5-4 m of water, 1-1.5 km from the mouths of Sleeper Log and Two Mile creeks (Figure 6.1).

The reefs at Paluma Shoals are developed upon a stable Pleistocene gravel substrate of unlithified granitic and volcanic clasts (Chapter 6). These reefs are bordered on their leeward margin by intertidal sands, an intricate system of shore-parallel intertidal sand bars and an extensive beach barrier complex. Behind the beach and beach barrier, mangrove-fringed tidal channels have developed with high-tidal salt flats between them(Figure 6.1). Muddy sands form a veneer of sediment between the reef shoals and extends seaward forming the modern bay fill (Chapter 6 & Figure 6.14).

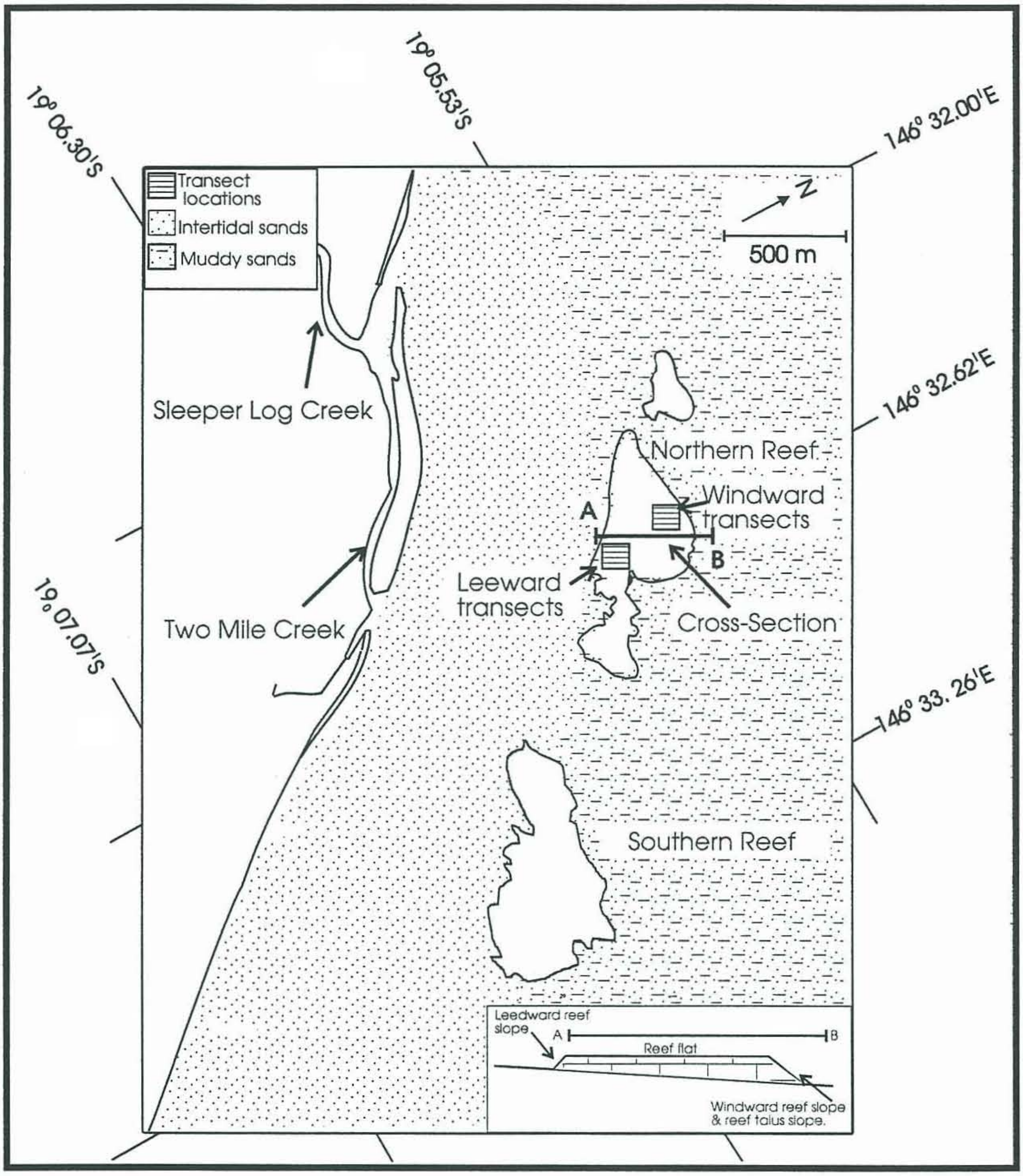


**Figure 4.1.** *Transect locations from Paluma Shoals and schematic cross-section. The grids represent the location of the transects from the windward and the leeward reef flat. Each 10 m transect were taken SW-NE or shore-normal.*

These reefs are irregular in plan view, are surrounded by terrigenous sediment and display classic spur and groove morphology. The larger of the two shoals (southern reef) is up to ca. 480 m wide and ca. 740 m in length (Figure 4.1). In an east-west cross-section (Figure 4.1) the leeward reef slope rises steeply (70-90$^0$) from the intertidal sands to the reef flat which slopes gently seaward to the windward reef slope (Watson, 1996). Gravelly muddy sands and gravelly sandy muds comprise the reef flat sediment which is punctuated by colonies of hard and soft corals. Stands of dark brown *Goniastrea* sp. on the leeward reef flat are emergent at low tide (Figure 4.2). The windward reef slope dips steeply (ca. 60-70$^0$) to the sea-bed which is composed of muddy sands with scattered *Turbinaria, Porites* and *Montipora* corals.

The Paluma Shoals reefs are interpreted as patch reefs because they are isolated from the main reef tract, are of limited scale and are completely surrounded by terrigenous sediment (Chapter 6) (Stoddart, 1969; Scoffin & Garret, 1974). Generally the morphology (which is irregular in plan) of the patch reef complexes adopt the overall geometry of the substrate (Pleistocene gravel deposits). Therefore, the development of the reefs at Paluma Shoals are restricted to the availability of the Pleistocene gravels. The emergent stands of *Goniastrea* at low tide indicate that the leeward edge of the reef flat has reached the upper-limits of vertical accumulation. The highly mobile muddy sands deposited between the patch reefs possibly inhibit further coral recruitment and reef development off the present reef platform.

### 4.3. Reef Morphology 2. Phillips Reef

Phillips Reef is situated ca. 15 km north of Paluma Shoals in water depths of ca. 16 m. Seismic data (Chapter 5) indicate that Phillips Reef is a 400 m wide (in a SSW-NNE direction) steep-sided flat topped-reef, which rises 6.75 m above the surrounding sea-bed (Figure 5.4). Surficial sediments windward and leeward of the reef are gravelly muddy sands (Chapter 6, Figure 6.14). Done (1982) details the gross morphology of Phillips Reef describing it as a shingle-covered reef developed upon submerged Permo-Carboniferous granite. According to the classification of Stoddart (1969), Phillips Reef is a patch reef.

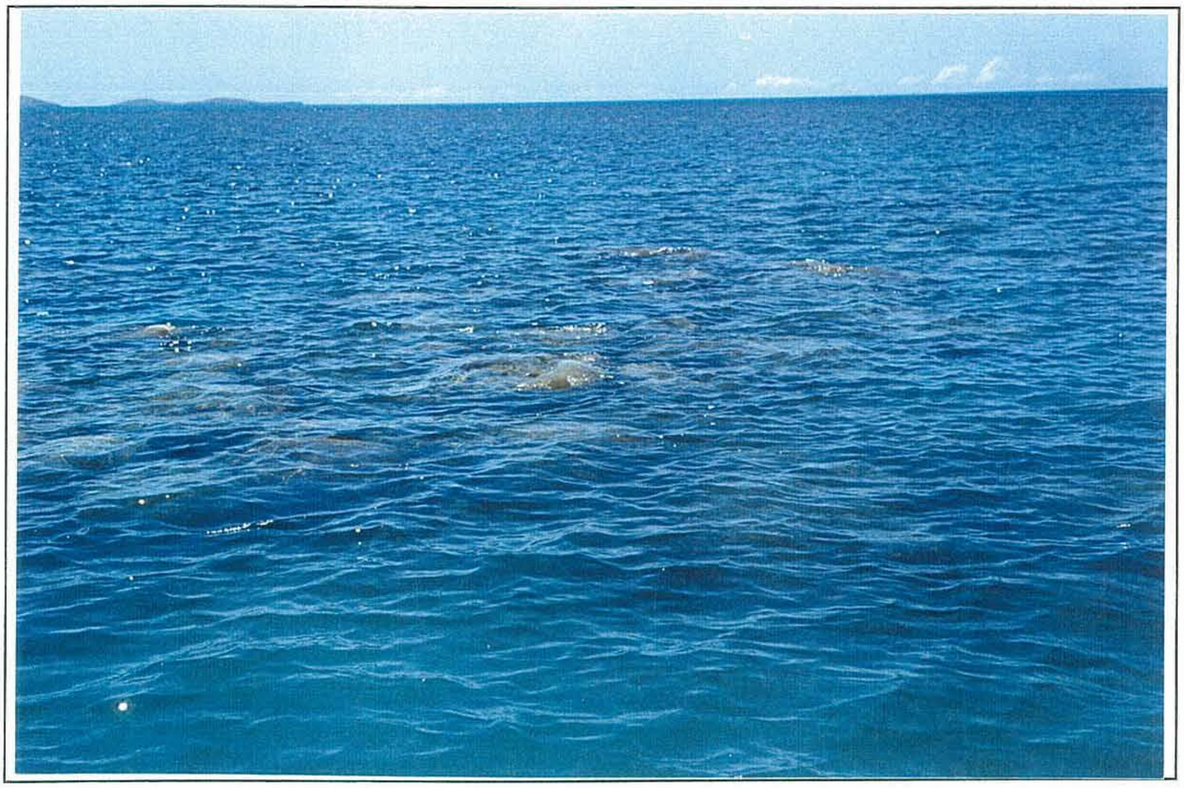

**Figure 4.2.** *Large stands of Goniastrea sp. emergent at a low tide 0.85 m on the leeward reef flat of Paluma Shoals looking seaward toward the windward reef flat. Herald Island is visible at the top left of the photograph. The emergent corals indicate that some of the coral has reached their vertical growth limits (Photograph. A.G.Gordy)*

### 4.4 Coral Taxonomy

A biological survey was undertaken (Watson, 1996) to evaluate the percentage cover of adult and juvenile corals at Paluma Shoals. These data were required to provide an account of the coral species present and to establish the "health" of the coral community. Field data was collected from the windward and the leeward side of the northern reef flat (Figure 4.1). Coral cover was assessed using the line-intercept transect method (Watson, 1996). Ten replicate, 10 m transects were surveyed from each site (Figure 4.1) by SCUBA. The linear intercept distances of each coral is converted into a proportion of space occupied along the transect (100 m total each site) giving percent cover estimates. The mean percentage cover with standard error (SE) of the various coral taxa are given for the two sites in Table 4.1 and summarised by family in Table 4.2. These data are not representative of the distribution of coral communities at Paluma Shoals because of the limited number of transects, however, some general trends emerged.

| | | W-reef flat | | L-reef flat | |
|---|---|---|---|---|---|
| Family | Genus sp. | mean | SE | mean | SE |
| Acroporidae | *Montipora* plating | 1.42 | 0.493 | 1.13 | 0.414 |
| Acroporidae | Digitate *Acropora* | 0.2 | 0.2 | 0 | 0 |
| Acroporidae | Branching *Acropora* | 1.15 | 0.551 | 1.32 | 0.497 |
| Poritidae | *Porites* branching | 0 | 0 | 6.49 | 1.581 |
| Poritidae | *Porites* massive | 0 | 0 | 1.77 | 0.99 |
| Poritidae | *Goniopora* | 0.9 | 0.545 | 0.3 | 0.3 |
| Faviidae | Faviidae | 1.3 | 0.622 | 2.9 | 1.916 |
| Faviidae | *Goniastrea* | 1.52 | 0.651 | 1.21 | 1.038 |
| Mussidae | Mussidae | 2.13 | 0.936 | 0.8 | 0.584 |
| Dendrophylliidae | *Turbinaria* | 0.9 | 0.397 | 0.72 | 0.213 |
| Fungiidae | Fungiidae | 0.26 | 0.133 | 0.24 | 0.183 |
| Merulinidae | *Merulina* | 0 | 0 | 0.06 | 0.06 |
| Oculinidae | *Galaxea fascicularis* | 15.92 | 2.666 | 36.21 | 3.706 |
| Caryophylliidae | Caryophylliidae | 0 | 0 | 0.17 | 0.125 |
| Alcyoniidae (softies) | *Lobophyton* | 0.25 | 0.171 | 0 | 0 |
| Alcyoniidae (softies) | *Sarcophyton* | 0.86 | 0.806 | 0 | 0 |
| Alcyoniidae (softies) | *Sinularia* | 1.06 | 0.345 | 0.12 | 0.12 |
| | total cover | 27.87 | 2.942 | 53.44 | 3.311 |

**Table 4.1.** Percentage *coral cover at Paluma Shoals calculated over ten x 10 m line intercept transects. Note that Galaxea fascicularis is the most abundant taxa on both the leeward reef flat (L-reef flat) and the windward reef flat (W-reef flat).*

The oculinid, *Galaxea fascicularis* occurring in large stands, was the most abundant coral intercepted on both transects, with 16 ±2.6 % cover at the windward reef flat and 36±3.7 % at the leeward reef flat (Watson, 1996). The total coral cover reflects this pattern, with total coral cover on the leeward reef flat (53.4±3.3 %) being almost twice that of the windward reef flat (27.9±2.9 %). Another difference between the two sites is the complete absence of *Porites* colonies (massive & branching) at the windward reef flat compared with a cover of 8 % at the leeward reef flat. Almost all of the other taxa present each occupied < 2% of available cover. Macroalgal cover was not quantified however, the abundance of *Pandina* sp. reflected a similar distribution pattern to that of the corals *i.e.* less abundant on the windward reef flat.

The presence of juveniles were recorded using the linear sampling technique (transect) which is more suited to cover estimates rather than number of colonies (Watson, 1996). The data which relate to the abundance of juveniles along the 100 m of transect at each site is presented in Table 4.2. These data are an indicator of coral recruitment.

| exposure | W-reef flat | | L-reef flat | |
|---|---|---|---|---|
| replicate trans | mean | SE | mean | SE |
| Acroporidae | 2.77 | 0.5 | 2.45 | 0.5 |
| Poritidae | 0.9 | 0.5 | 8.56 | 1.2 |
| Faviidae | 2.82 | 0.6 | 4.11 | 1.5 |
| Mussidae | 2.13 | 0.936 | 0.8 | 0.584 |
| Dendrophylliidae | 0.9 | 0.397 | 0.72 | 0.213 |
| Fungiidae | 0.26 | 0.133 | 0.24 | 0.183 |
| Merulinidae | 0 | 0 | 0.06 | 0.06 |
| Oculinidae | 15.92 | 2.666 | 36.21 | 3.706 |
| Caryophylliidae | 0 | 0 | 0.17 | 0.125 |
| Soft corals | 2.17 | 0.8 | 0.12 | 0 |
| Total | 27.87 | 2.942 | 53.44 | 3.311 |

**Table 4.2.** *Percent coral cover by family at Paluma Shoals calculated over ten x 10 m line intercept transects.*

| Juvenile corals | | |
|---|---|---|
| Taxa | W-reef flat | L-reef flat |
| Branching Acroporidae | 0 | 2 |
| Faviidae | 3 | 4 |
| Faviidae; *Goniastrea* | 1 | 0 |
| Poritidae; *Goniopora* | 2 | 0 |
| Alcyoniidae; *Sinularia* | 2 | 0 |

**Table 4.3.** *Abundance of juvenile corals encountered along 100 m of transect from each site (ie. Sum of ten x 10 m transects).*

Done (1982) described the coral community at Phillips Reef and classified it as a Class 3 community, characteristic of inner-shelf or sheltered habitats. His classification scheme is based on exposure to wave energy, with Class 1 communities centered around the maximum wave energy areas (outer-reef tract) and Class 2 in semi-exposed to sheltered habitats (Done, 1982). Done (1982) notes that Class 3 communities bear little resemblance to those of the mid and outer-shelf reefs with species and community diversity both greatest in these offshore communities. The coral taxa characteristic of Class 3 communities are:

- *Acropora splendida/divaicata*
- *Montipora/Pachyseris*
- *Galaxea*
- *Montipora*
- *Goniopora*

Done (1982) notes that the upper windward slope of Phillips Reef is occupied by a *Sargassam*-dominated macro-algae community plus a co-inhabiting *Montipora* coral community (distribution ~20 %). The lower and middle sections of the flank and leeward slopes are occupied mainly by the *Goniopora* community. The shallower leeward and flank slopes are occupied by the *Porites* "massive/branching" community with extensive monospecific stands of *Pavona cactus*, *Alveopora catalai*, *Echinopora lamellosa*, *Turbinaria* spp and soft corals.

The data collected from Paluma Shoals can only loosely classify these reefs according to Done (1982) *ie.* place them into the Class 3 category. However, some broad comparisons can be made between Phillips Reef and Paluma Shoals using the quantitative data, and direct observations of the reefs during numerous dives. These include the presence of all taxa which comprise a Class 3 community (Table 4.1). Direct observations during dives revealed corals ranging in size from < 5 cm (juveniles) to > 3 m in diameter including vast stands of *Acropora (staghorn) Acropora (Digitate) Galaxea fascicularis* and *Mussidae* corals (Figure 4.3) Massive *Goniastrea* sp., *Porites* sp. and *Favidae* sp. coral heads of considerable girth are common. (Figure 4.2 and Figure 4.4) These taxa are characteristic of communities from sheltered shallow water reefs and lagoons (Done, 1983) and are similar to those described by Done (1982) at Phillips Reef. With the presence of juveniles (< 5 cm in diameter) and arrays of unbleached corals ranging up to 3 m in diameter, it is possible to assume that the corals at Paluma Shoals form a healthy, diverse population.

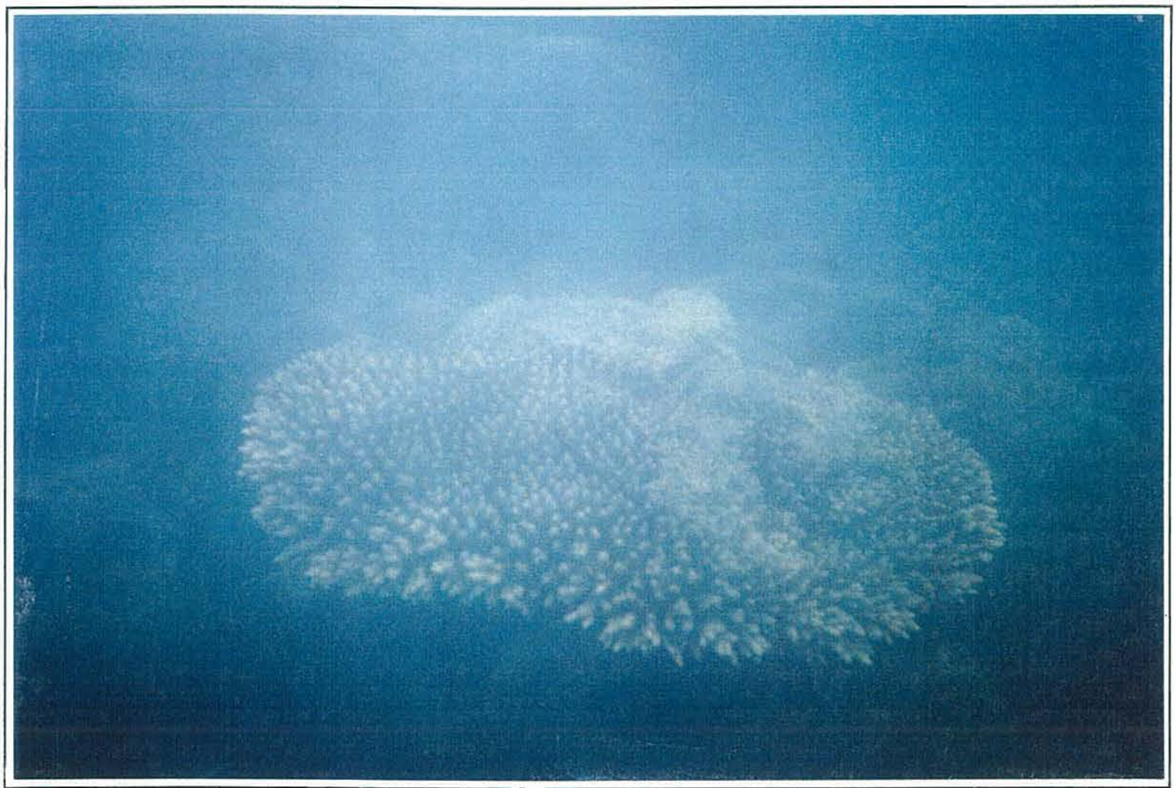

**Figure 4.3.** *Large Acropora (Digtatae) colony from the leeward reef flat at Paluma Shoals. Photograph was taken at a depth of 2 m with visibility ca.2 m, colony ca. 2.5 m across.*

**Figure 4.4.** *Large* *Favidae* *colony (brain coral) from the windward reef flat of Paluma Shoals. The colony is surrounded by turfing algae (foreground). Photograph taken at ca. 3 m with visibility of ca. 2.5 m, colony ca. 1.5 m across.*