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SEDIMENTOLOGY OF FRANK SOUND AND PEASE BAY, TWO MODERN SHALLOW-WATER HURRICANE-AFFECTED LAGOONS, GRAND CAYMAN, BRITISH WEST INDIES

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled SEDIMENTOLOGY OF FRANK SOUND AND PEASE BAY, TWO MODERN SHALLOW-WATER HURRICANE-AFFECTED LAGOONS, GRAND CAYMAN, BRITISH WEST INDIES submitted by WILLIAM B.C. KALBFLEISCH in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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DEDICATION

Friends and family.

ABSTRACT

Frank Sound and Pease Bay are small narrow (~ 4 km long and < 1 km wide) shallow water (1.5 – 2.0 m average depth) lagoons bound by land or nearly continuous shallow reef (< 0.5 m deep) located on the unprotected windward south coast of Grand Cayman. Although wave driven currents over reef during fair–weather conditions maintain good lagoonal water circulation (e.g., salinity and temperature are near open ocean levels), wave energy is largely reduced by the reef and has little effect on lagoon sediment or biota. Fair–weather processes are limited to local sediment production (e.g., *Thalassia* epibionts, bioerosion, green algae), bioturbation, and *Thalassia* colonization.

Hurricane and severe storm processes greatly overprint fair–weather processes and control sediment and biota distribution. Based on hurricane effects, the lagoons can be divided into 1) *areas of sediment deposition*, characterized by the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones, and 2) *areas of sediment erosion*, marked by the Bare Rock Zone.

During the height of a hurricane, storm waves and currents passing over the reef will result in a turbulent sediment laden current crossing the lagoon. As the current loses energy, deposition produces a sediment wedge grading from boulders – cobbles (near reef crest), to pebbles and coarse sand (~ 80 m from the reef crest), to fine sand (at least 500 – 600 m from the reef crest). This sediment is consistently poorly sorted and has a unimodal grain size distribution. Silt and clay sized sediment is rare. Constituents indicate most of the lagoon sediment originates from the fore–reef and shelf environs. Lagoon biota change from brown algae and coral colonizing the back–reef rubble, to

green algae in the storm agitated bare sand, to a *Thalassia* community ~ 300 – 400 m from the reef crest where storm energy is low enough for *Thalassia* to resist rip up.

As the storm passes, the lagoons drain storm piled water through topographically controlled mega–rip currents. These high velocity currents destroy biota and strip sediment, resulting in bare rock substrate and other erosional features.

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Many thanks go out to the staff of the Natural Resources Laboratory, Department of the Environment, of the Cayman Islands for their support and generous loan of equipment. I would especially like to thank Phillip Bush, Scott Slaybaugh, and Mike Grundy for their time and advice.

Special thanks to my dive buddy Peter Kalbfleisch, for his *dedication* and *courage* beyond the call of duty... and sanity. ("Well Pete, for a change, I thought we might swim 3 km against a current in a lightening storm dragging 30 kg of sand, 4 m of metal rod (sticking straight up in the air), an air-powered drill, a SCUBA tank, and various other loose and buoyant implements. What do ya' think?")

Thanks also to the Modern Carbonate Research and Coffee Break Group;

Paul "Doomsayer" Blanchon	"Blah, blah, blah, hurricanes, blah, blah, *Acropora*, blah, blah, blah, Mega-floods, blah, blah, blah, sea-level rise, blah... (pause) — Totty!!!"
Chun "Foram-Master" Li	"Oh dis' is Bullsheet. I have foram in my eye and my pants. Dey everywhere."

Thanks to my other friends for their insight and for being friends;

Brent Wignall	"It's a powerful combination."
Jennifer "The Nose" Vézina	"Ewwwe, it smells like boys in here."
Ian "Foofty" Hunter	"Whaa? I didn't ask."
Kenton "Big Man" Phimester	"Bill-Fish, you are very straaange..."
Jason "Tex" Montpetit	"Tex, if I were a sedimentologist, and you were my lady, would you marry me anyway, ...?"
Dave "Toaster-Boy" Hills	"Tex! The toast Tex! The toooooast!"
Leo "Pig-oli" Piccoli	"Li screwed up the printer!"

Lastly, I would like to express my gratitude to Dr. Brain Jones for his helpfull sugestions, and keen editorial sills. This research was supported by a NSERC grant to Dr. Jones (A6090).

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I. INTRODUCTION

A. INTRODUCTION

The term lagoon has been widely applied to a variety of geomorphic features and environments. As a result, the term has suffered a loss of concise meaning. In this study a lagoon is defined as a shallow body of subtidal marine or near marine water, typically less than 10 m in depth, that is isolated from, but connected to, the open ocean, and is nearly enclosed by a combination of barriers or land. The interior of an atoll or the area between a fringing reef and land are examples of lagoons. By this definition a lagoon is typically smaller and more dependent on the adjacent ocean for water energy, circulation, and water chemistry than rimmed platforms.

Lagoons appear at first to be tranquil environments that are protected from the strong currents, waves, and tidal energy present on the open shelf. As a result, lagoons are expected to contain *in situ* deposits of biologically produced sediments with a high content of fine-grained material. Polymodal grain-size distribution is also expected in biologically dominated areas, with each mode corresponding to a main breakdown size of the source organisms. Such a polymodal sediment was described in Folk and Robles' (1964) classic study of Isla Perez beach sands. Grain-size parameters such as mean, sorting, and skewness are anticipated to vary with the biological community present.

In contrasting to sediments developed in a low energy, biologically dominated system are those developed under high water energy systems. Biological grain-size modes would be suppressed through sediment reworking by currents and waves. A simple one energy source grain-size distribution is unimodal, with variation in mean grain-size and sorting relating directly to changing energy.

Frank Sound and Pease Bay, Grand Cayman (Fig. 1.1), the focal areas of this study, are examples of lagoons with sediments belonging to the high energy dominated system. Under fair–weather conditions, the reef fronting each lagoon acts as an effective barrier to energy from the ocean (Roberts *et al.*, 1975; Roberts, 1988). Although in localized areas high current and wave energy can effect lagoon sediments, the determining factor in sediment production is *in situ* biological production. Caribbean weather, however, is not always pleasant. Clark (1988) determined that hurricanes passed directly over the island with a frequency of one every 9.2 years. Hurricane Gilbert, in 1988, was the last hurricane to pass directly over Grand Cayman. It had winds exceeding 130 mph, yet damage to property and vegetation was minor. Historic records describe much more severe storms in 1846 and 1910. Eyewitness accounts described the sea completely passing over the island between the South Sound and North Sound, a distance of 1.2 km (Burton, 1994). Waves > 3 m were described at the reef crest of South Sound (Roberts, 1988; Clark, 1988). It is not difficult to imagine that during such abnormal conditions significant wave energy can pass over the reef and into the normally quiescent lagoons. Such severe conditions rapidly rework the sediment destroying, overprinting, or otherwise obscuring any sedimentary patterns (i.e., polymodal grain–size distribution, biologically related patterns in mean grain–size and sorting) acquired in normally placid lagoon waters.

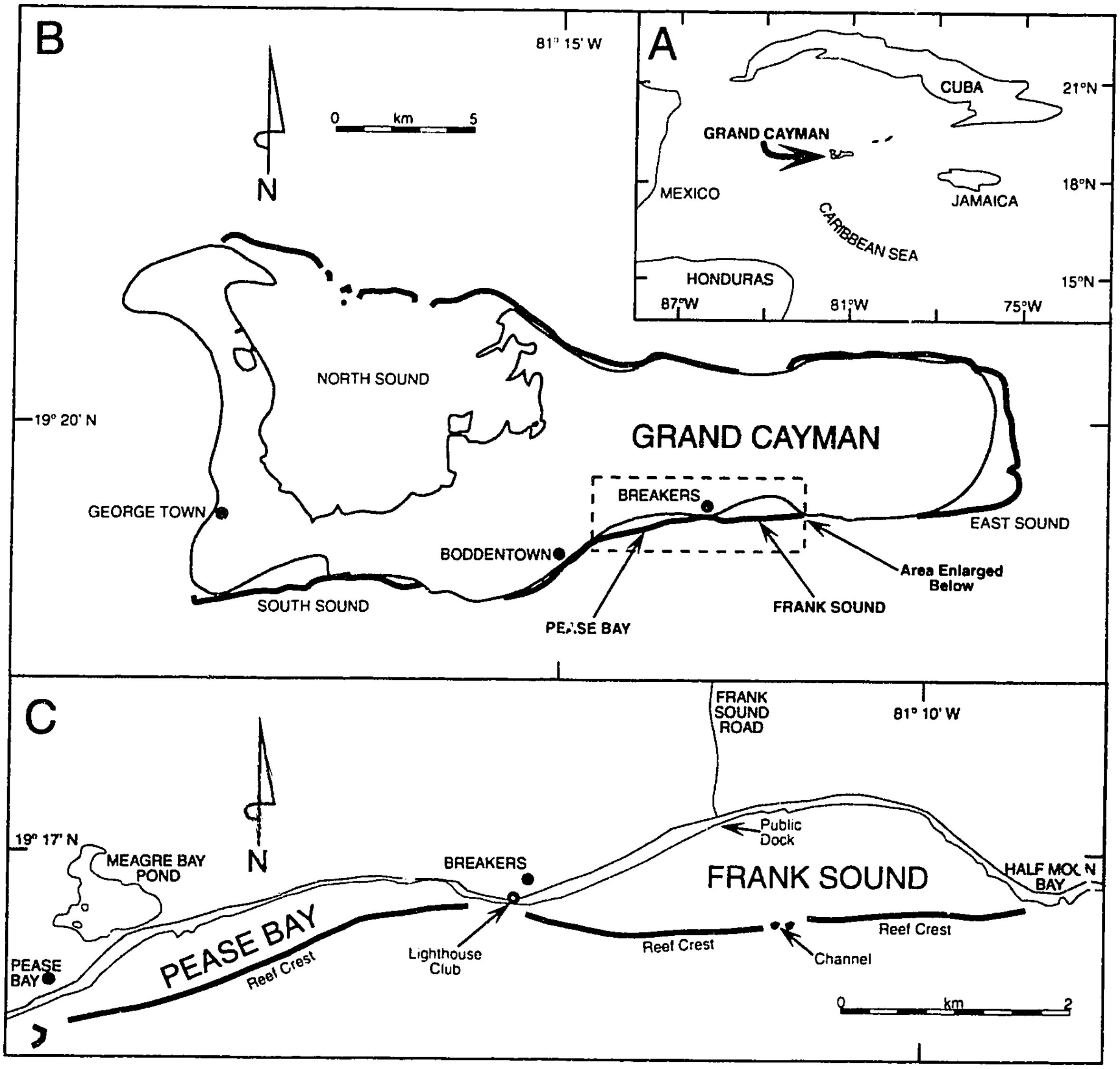


Figure 1.1: (A) Location map of Grand Cayman. (B) Location map of Frank Sound and Pease Bay. (C) Map of Frank Sound and Pease Bay.

B. OBJECTIVES

This study involves a detailed examination of two lagoons on the south coast of Grand Cayman that are relatively tranquil during fair–weather and subject to high water–energy during storms. Through a study of substrate and bottom–community distribution, and sediment grain–size and component analysis, this study will assess,

1) the factors controlling the distribution of sediment and biological communities, and

2) weigh the relative importance of fair–weather versus storm processes in the formation of lagoon sediments.

C. TECTONIC SETTING

Grand Cayman, located south of Cuba and north–northwest of Jamaica (Fig. 1.1A), is the largest of three islands that are high points on the Cayman Ridge which stretches from the Sierra Maestra range in southwestern Cuba to the Misteriosa bank (Fig. 1.2A; Brunt *et al.*, 1973). The Cayman Islands lie on a base of granodiorite that is overlain by basalts and Tertiary carbonates (Emery and Milliman, 1980; Stoddart, 1980). The total thickness of the carbonate succession is unknown. Two wells in the central part of Grand Cayman, however, were still penetrating carbonates at 401 m and 159 m (Emery and Milliman, 1980).

Subsidence began in the Oligocene to Miocene at a rate of 6 cm/1000 yr (Perfit and Heezen, 1978) to 10 cm/1000 yr (Emery and Milliman, 1980). After the Middle Miocene, the Swan Islands, Cayman Islands, Jamaica, and most of southern Cuba were uplifted whereas neighboring areas continued to subside (Perfit and Heezen, 1978). The

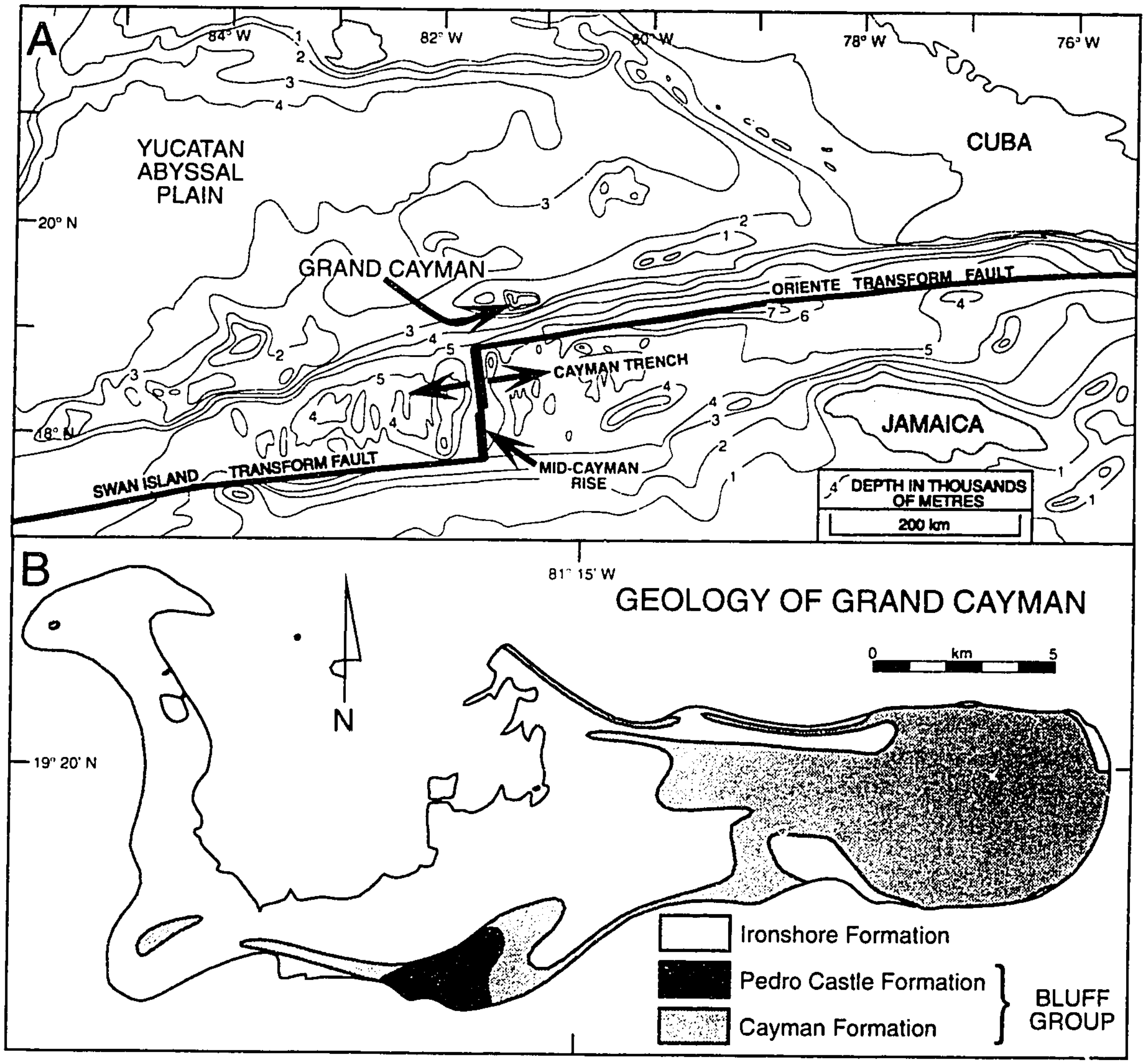


Figure 1.2: (A) Tectonic setting of Grand Cayman (modified from Pleydell et al. (1990) and based on information in Perfit and Heezen (1978) and Halcombe (1978)). (B) General surfical geology of Grand Cayman (modified from Jones *et al.*, 1994b).

fault blocks on which the Cayman Islands are located, remained unstable and were subjected to differential vertical movement until the last interglacial period (Woodroffe *et al.*, 1980). Since then the Cayman Islands have undergone little vertical movement (Emery, 1981; Jones and Hunter, 1990).

D. GENERAL GEOLOGY

The Bluff Group, which forms the core of Grand Cayman, is unconfomably surrounded and partly overlain by the Pleistocene Ironshore Formation (Fig. 1.2B; Matley, 1926; Brunt *et al.*, 1973; Rigby and Roberts, 1976; Jones and Hunter, 1989; Jones *et al.*, 1994b).

The Bluff Group consists of three unconformity–bounded packages; the Brac, Cayman, and Pedro Castle formations (Jones and Hunter, 1989; Jones *et al.*, 1994b). The Brac Formation (L. Oligocene) is a limestone, or fabric destructive sucrosic dolostone with pods of limestone, that has only been found on Cayman Brac (Jones *et al.*, 1994a). Some limestones show no evidence of dolomitization whereas others are pervasively replaced. The Cayman Formation (L. – M. Oligocene), which outcrops over much of Grand Cayman (Fig. 1.2B), consists of a microcrystalline fabric–retentive dolostone (Jones *et al.*, 1994b). The Pedro Castle Formation (L. Pliocene) is formed of limestone, dolomitic limestone, and dolostone (Jones *et al.*, 1994b). The fabric retentive dolostones are similar to those in the Cayman Formation.

The Ironshore Formation (125,000 years old) is a shallowing–upwards sequence of poorly consolidated limestones cemented by calcite. A subtidal lagoonal facies at the base of the sequence is overlain by the lower shoreface facies, to the upper shoreface facies, to the foreshore–backshore facies. Most of the limestones were deposited in a lagoonal environment during the last interglacial period when sea–level was 6 m above the present sea–level (Jones and Hunter, 1990).

E. PHYSICAL GEOGRAPHY

Grand Cayman has a land surface area of about 196 km^2. It is 35 km long (east–west), 6 km wide in the east, and 14 km wide in the west (Fig. 1.1B). Most of the island is less than 3 m above sea–level. The maximum elevation of 18 m above sea–level is on the "Mountain" located in the north–central part of the island (Fig. 1.3). Approximately 50% of the land surface of Grand Cayman is covered by brackish water mangrove swamp (Mather, 1972; Proctor, 1984). The remaining surface area is covered by rugged karst terrain with patchy soil and dense vegetation (Jones and Smith, 1988), land cleared for agricultural use, and urban areas. Most of the population of Grand Cayman lives on the western half of the island.

A low relief *peripheral ridge*, formed of dolostones belonging to the Cayman Formation, is present along the north, east and south shores of the island (Fig. 1.3; Jones and Hunter, 1994). The ridge is most pronounced along the east and northeast coasts where it can exceed a 10 m height. Inland from Frank Sound and Pease Bay the ridge is not as conspicuous nor as continuous. The ridge is > 6 m at the eastern end of Frank Sound near Half Moon Bay and is > 10 m at the eastern end of Pease Bay near Breakers (Fig. 1.3; profile C–D).

The most prominent feature of Grand Cayman is North Sound (Fig. 1.1B), a dish shaped lagoon located on the west end of the island. North Sound is approximately 10 km

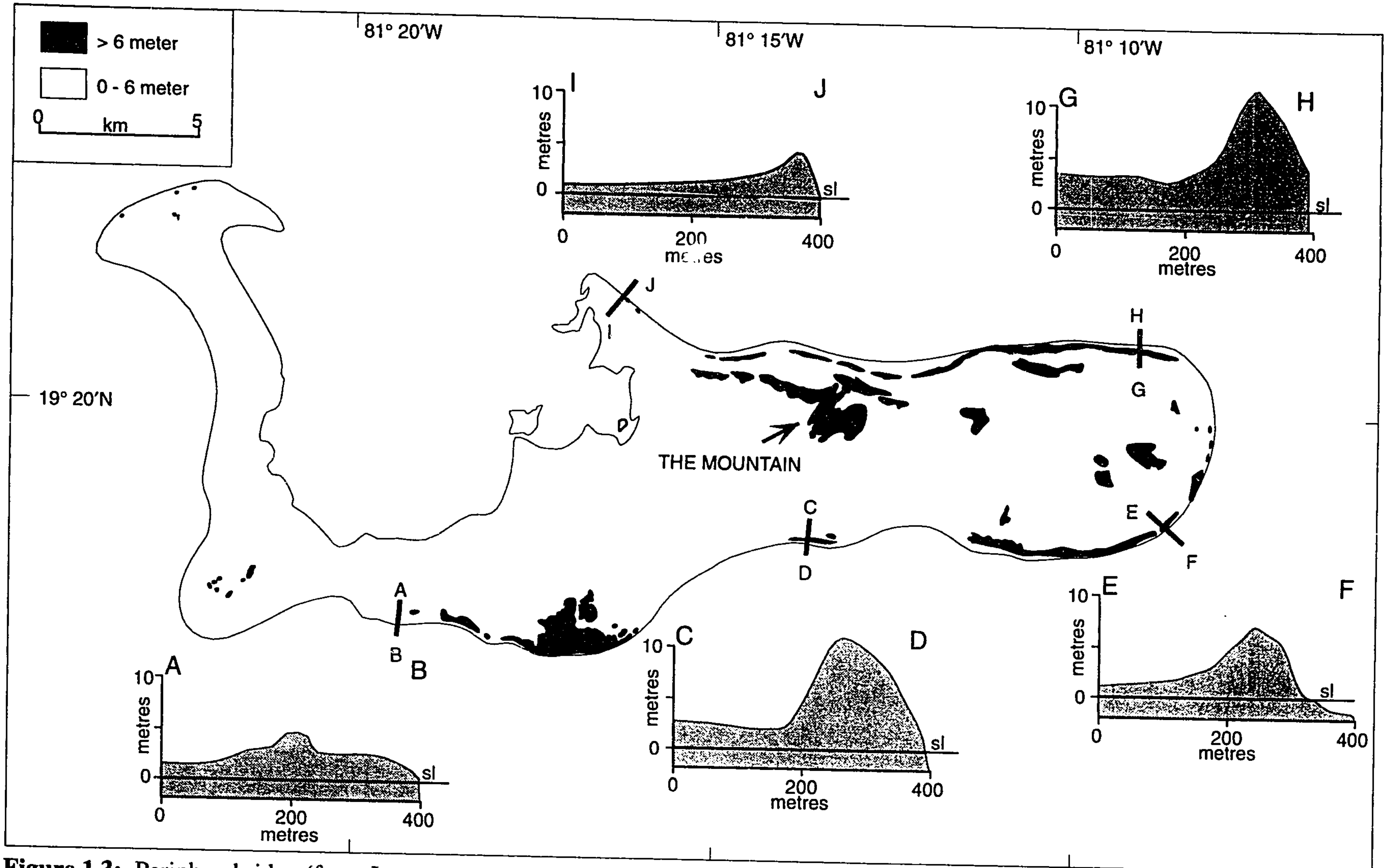


Figure 1.3: Peripheral ridge (from Jones and Hunter, 1994).

in diameter with water depths generally less than 5 m (Roberts, 1976). North Sound is bound by reef in the north and mangrove swamps or urban areas on all other sides. The north, south, and east sides of the island are fringed by nearly continuous reef; smaller coastal lagoons, with water depths generally less than 3 m, may be present behind this reef. On the north side of the island, narrow lagoons (< 1/2 km wide) are located between the fringing reef and shore. The south coast has three major coastal inundations, South Sound, Pease Bay and Frank Sound, that are enclosed on the seaward side by reefs that stretch from headland to headland. The east end of the island has a broad lagoon that extends, at the widest point, nearly 2 km from shore and is rimmed by reef. The west shore of Grand Cayman, the leeward side of the island, lacks a fringing reef and lagoon (Blanchon and Jones, 1995).

F. PREVIOUS STUDIES: LAGOONS OF GRAND CAYMAN

Early geological investigators of Grand Cayman only mentioned the presence of shallow water lagoons in coastal inundations around the island (Matley, 1926; Doran, 1954). Doran (1954) described the fringing reef as a "structureless ridge, dead and stony in appearance" composed primarily of dead coral and coral cobbles, which encloses narrow lagoons. He also noted the lagoon floor of North Sound is mainly exposed bedrock or a thin veneer of sediment colonized by *Thalassia* sea grass.

The single largest body of work pertaining to the lagoons of Grand Cayman was produced by Dr. H. Roberts during the 1970's. Concentrating on North Sound, he determined the major sound environments and organic communities (Roberts, 1971a) and mineralogic variation of lagoonal sediments (Roberts, 1971b). Island wide marine environments were considered in Rigby and Roberts (1976) and the previous North Sound studies were expanded in Roberts (1976). Marine environments in North Sound were divided into lagoonal, dominated by the "Grass Plain", and reef shoal environments, including the "Reef Crest", "Rubble Flat", "Moat", "Rock Floor", and "Sand Flat". Sediments from the lagoonal substrates were largely composed of *Halimeda* and Foraminifera, whereas the reef shoal sediments were dominated by coral, *Halimeda*, and mollusks.

Roberts also studied fair-weather wave and tidal current systems around the island (Roberts *et al.*, 1977) and related these to the coral distribution on the open shelf (Roberts, 1974), the fringing reef systems (Roberts *et al.*, 1975; Suhayda and Roberts, 1977), and open shelf sediment accumulation (Roberts, 1983). He described an overall westward current which effects the open shelf and, to a lesser extent, the fringing lagoons. He also found that open ocean wave height was reduced by 20% crossing the narrow shelf (~ 0.4 km) and 75% by breaking on the fringing reef crest which protects the lagoons (Roberts *et al.*, 1975). Wave energy breaking over the fringing reef crest was determined to be the major driving force of currents in South Sound, and current strength was related to sediment thickness (Suhayda and Roberts, 1977, Roberts, 1981).

Results from Roberts work on Grand Cayman are summarized in a series of geologic field guides (Roberts and Moore, 1972; Roberts, 1977; Rigby and Roberts, 1976; Roberts and Sneider, 1982).

Raymont *et al.* (1976) conducted a major biological survey of Grand Cayman's marine environments including North, South, and East Sounds. South Sound, which most closely resembles the areas important in this study, was found to have a large expanse of *Thalassia* sea grass near shore, which gives way to sand, rubble, and coral near the reef crest. The dominant flora was *Thalassia* near shore, green algae on the sand plain, and brown algae on the rubble substrate.

The most recent work pertaining to Grand Cayman's lagoons was a remote sensing study by Tongpenyai (1989) and Tongpenyai and Jones (1991). Using aerial photographs and image analysis they delineated the major lagoonal substrates, and measured the extent and changes over time of each substrate. They showed that *Thalassia* grass is expanding at the expense of bare sand substrates.

To date, research in the lagoons of Grand Cayman has concentrated on the biological and environmental aspects, and little work has been done on the processes effecting the lagoon substrates. Roberts' work discussed fair–weather wave and current energy in North and South Sound yet never clearly related this to the lagoon sedimentology. What is more important, the effects on lagoon sedimentology of the largest, most devastating force in the Caribbean — the hurricane — was never accessed.

II. MATERIALS AND METHODS OF STUDY

A. FIELD METHODS

Nine transects, 150 m to 470 m long, were made in Pease Bay followed by seven transects, 470 m to 975 m long, in Frank Sound (Fig. 2.1A, B). Transects were made using compass bearings and by lining up shoreline features with reference poles and buoys on the transect. Features recognized on recent air photographs and in the field were used to check accuracy. Water depth, sediment thickness, and a description of the substrate was recorded every 10 m. Substrate descriptions include conspicuous flora, fauna, and sediment characteristics including ripples, shrimp mounds, and rubble. Sediment thickness was determined using a probe that was driven into the sediment by an air powered drill. Underwater photographs were taken of representative substrates and significant bottom features.

Sediment samples were collected at 30 m intervals along four transects in Frank Sound (Fig. 2.1A) and at 20 – 30 m intervals along five transects in Pease Bay (Fig. 2.1B). At each station 0.5 – 1 kg of sediment was scooped into pre-numbered bags.

Further water depth measurements were made in Frank Sound using a shipboard recording depth sounder (Fig. 2.1A) (Lowrance X-19, Lowrance Inc.) and a Global Positioning System for accurate coordinates (Magellan GPS Nav 5000, Magellan Systems Corporation). Pease Bay lacks a channel wide enough for ship access so depth soundings were not possible. Sediment thickness could also be determined from the depth sounder records where the soft sediment was penetrated by the depth soundings. Accuracy for this

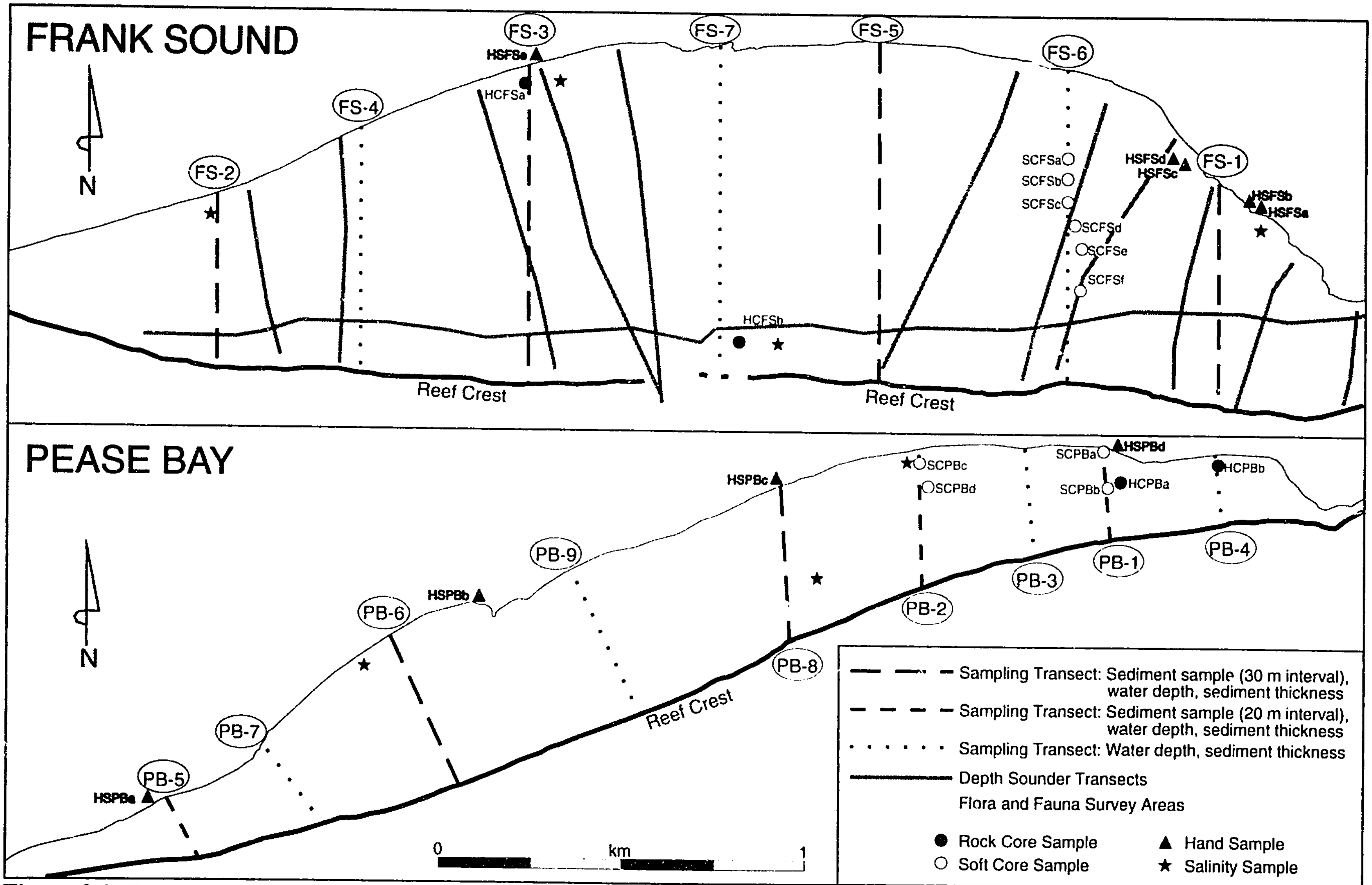


Figure 2.1: Transect and sample locations in Frank Sound and Pease Bay.

method was estimated at ± 15 cm by comparing areas of known sediment thickness to the depth sounder records.

Sediment cores were collected by driving four inch (10 cm) diameter PVC pipe into the sediment using the method outlined by Jones *et al.* (1992) or by hammering the PVC pipe into the sediment. Four short cores were taken in Pease Bay and six cores, 0.70 to 1.65 m long, were obtained along a transect in Frank Sound (Fig. 2.1). The longest core collected came within 5 cm of bedrock and penetrated 97% of the sediment pile. More typically however, cores covered between 60 – 80% of the sediment pile because coring was stopped by coarse sediment, boulders, or friction. The PVC pipe was cut using a saw and the core split using a thin wire and a knife. Sediment samples were taken at 10 or 20 cm intervals in cores SCFSa, SCFSd, and SCFSf.

Rock samples were collected to determine the bedrock of the lagoons. Shoreline outcrops were sampled and rock cores were drilled offshore in both lagoons (Fig. 2.1). Bedrock cores were drilled using a compressed air drill with a 4 cm diameter, 1 m long core barrel. Four rock cores were obtained from Pease Bay and Frank Sound. The cores were 0.12 to 0.95 m long.

Salinity was measured in four locations in Frank Sound and three locations in Pease Bay near–shore and offshore (Fig. 2.1) and compared to an open ocean sample from offshore Georgetown.

A flora and fauna survey was conducted for the two most important types of substrate found in Frank Sound and Pease Bay. Conspicuous surface biota found in a randomly placed 1 x 1 m grid were identified and counted. Seventy–nine and twenty–

eight grids were counted from the bare sand and grass substrates, respectively (Fig. 2.1). In addition a visual surveys of all types of substrates in both lagoons was conducted and reference samples of carbonate producing organisms were collected.

B. GRAIN–SIZE ANALYSIS

Grain–size analysis of 71 surface sediment samples and 18 samples from sediment cores was conducted using the procedures described by Folk (1968). Samples estimated to contain less than 5% silt and clay were rinsed three times in distilled water and air dried. Samples with an estimated silt and clay content greater than 5% were left in sample bags without drying and approximately 20 ml of formaldehyde was added to prevent aggregation and decay during transportation.

Sediment containing large amounts of gravel or coarser material (> 15%) were limited to the area immediately behind the reef crest. Given the restrictions of time in the field, the large sample size required for ideal grain–size analysis of coarse material, and problems associated with accurate collection of large samples, the quantitative analysis of these sediments was not attempted. In areas where coarse sediment is dominant, samples of the sand fraction were collected and sieved for comparison with other areas.

After returning from the field, wet samples were mixed into a slurry and poured into a 63 μm sieve. A pan collected the fine material that passed through the sieve. Distilled water was run over the sample until the water passing through the sieve was clear. The sample was concentrated by evaporation, siphoning, and centrifuge. The material that was captured by the sieve was dried and later sieved.

The size distribution of the silt and clay was determined using a SediGraph 5100 (v. 3.01) by lab technicians of the Department of Geography, University of Alberta. Data acquired from sieve analysis and SediGraph analysis were joined using the methods described in Coakley and Syvitski (1991).

All of the samples taken on transect FS–1 were sieved at 1/4 ϕ (phi) intervals from –2 to 4 ϕ. Using 1/4 and 1/2 ϕ intervals, statistical parameters were calculated and compared. Graphical mean and standard deviation (sorting) did not show enough variation to justify 1/4 ϕ intervals for all the samples sieved. Additional samples were sieved at 1/4 ϕ where detail was required and at 1/2 ϕ where only basic statistical parameters were required.

Variations in screen openings from the ideal is a possible source of error in sieve analysis that can be corrected by screen calibration (Folk, 1966; Dalsgaard, *et al.*, 1991). Folk (1966) suggested screening a sample of know normal distribution, graphing the results, noting any "shoulders" or variations from the normal distribution. Similarly, Dalsgaard *et al.* (1991) suggested screening a series of samples from different localities and with different size distributions and compare the results for kinks in the size distribution at the same size fraction. Both of these tests were performed on samples from the study area. Nine beach sand samples were sieved and compared for the first of these tests because they typically exhibit a normal or near normal particle distribution. The second test compared the results from samples spanning the three major lagoon substrates and a beach sample, collected on transect FS–1. In both cases no major and consistent "kinks" in the size distribution curves were observed therefore any kinks found in individual samples arise from real traits of particle grading.

Some of the dried grains became aggregated. The percentage of aggregates was determined for each size class by counting the number of aggregated grains in one hundred grains. The percentage of aggregates was subtracted from the weight of each size class.

Samples with > 5% silt and clay sized particles and the coarse fraction from wet–sieving samples for the SediGraph were dry sieved was using a Ro–Tap shaker and a new set of W. S. Tyler Canadian Standard sieves. Cumulative weight percents were calculated from all samples analyzed and the values were plotted on probability graphs. The 5th, 16th, 25th, 50th, 75th, 84th and 95th percentiles were determined from these graphs and used to calculate the mean and median grain–size, sorting, and skewness as defined by Folk and Ward (1957; Table 2.1).

C. SEDIMENT COMPONENT ANALYSIS

Suites of thin sections were made from, 1) surface sediment samples, 2) samples from sediment cores, 3) sample of sieve fractions, and 4) samples of known fragments. Sediment from each sample was imbedded in epoxy and standard thin sections were prepared from the epoxy plugs. Thin sections of sieve fractions were made using a 3 x 5 plastic grid (a 7.5 x 4.5 cm piece of fluorescent light cover panel), adding 1/2 ϕ sieve fractions to each section, impregnating the grid with epoxy, and preparing standard sections from the epoxy blocks.

Identification of constituent components was made with the aid of descriptions provided by Ginsburg (1956), Purdy (1962a), Bathurst (1971), and Roberts (1976), and by comparisons with thin sections prepared from known fragments. Grains were counted using an automatic point counter and stage and a grid from 0.3 by 0.3 mm to 1 by 1 mm depending on grain–size. At least 300 grains were counted from each sample. Ginsburg (1956) suggested that such a method is accurate to ±5%.

III. PHYSICAL ENVIRONMENT

A. CLIMATE

Grand Cayman is located in the western part of the Caribbean and experiences a tropical climate primarily influenced by the moisture–laden easterly Trade Winds. Daily average temperature ranges from winter lows of 25.2°C (January – February) to summer highs of 28.5°C (July – August) (Jones and Goodbody, 1984). Winter storms from the north–west can result in cold fronts with temperatures as low as 12.8 to 15.5°C (Rigby and Roberts, 1976).

Winds on the island are dominated by the easterly Trade Wind belt and average 3 – 7 m/sec (Darbyshire *et al.*, 1976). During fair–weather conditions, wind direction is from north–northeast to east–southeast shifting seasonally from the northeast during the winter months to east and south–east during the summer (Fig. 3.1A). Summer storms approach from the south–east. Winter "Nor' Wester" storms approach from the north–northwest for a few days and can occur from mid–September to mid–March. Under this wind regime the west side of island is leeward, all other sides are windward.

The rainy season on Grand Cayman is from May to October (Fig. 3.2). The island has an irregular precipitation distribution with the northeast end of the island receiving significantly less precipitation than the southwest (Fig 3.1A and Fig. 3.2). The Tortuga Club received an average annual rainfall of 1059.6 mm whereas Southwest Point received 1330.3 mm, between 1986 – 1993 (data collected by Natural Resources Grand Cayman). Frank Sound and Pease Bay are situated between Bodden Town and East End which have

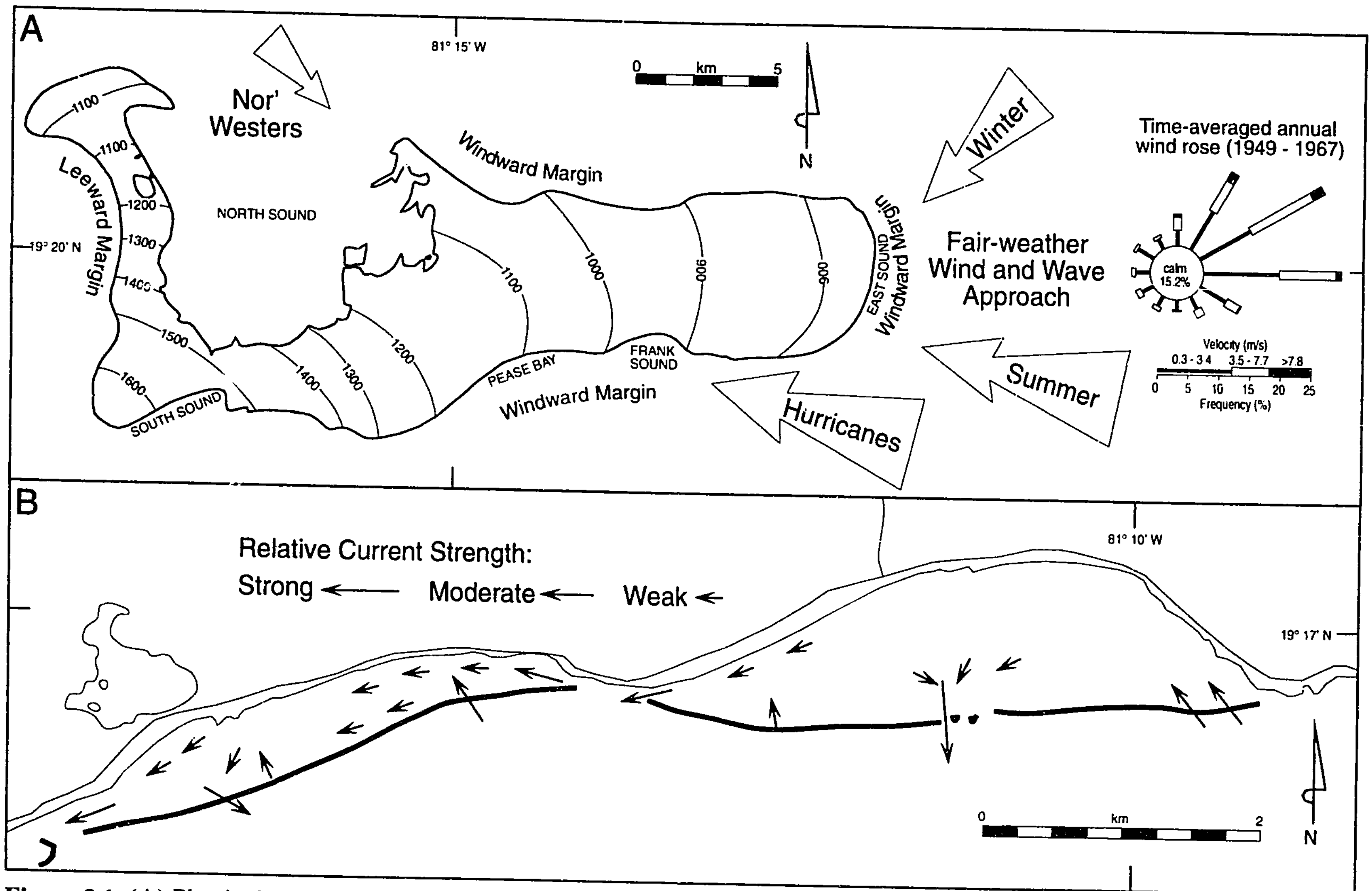


Figure 3.1: (A) Physical environment of Grand Cayman. Wind and storm directions (from Darbyshire *et al.*, 1976) and isohyets (mm) of average precipitation for 1987 (from Ng *et al.*, 1992). (B) Relative circulation map for Frank Sound and Pease Bay (from Rigby and Roberts, 1976).

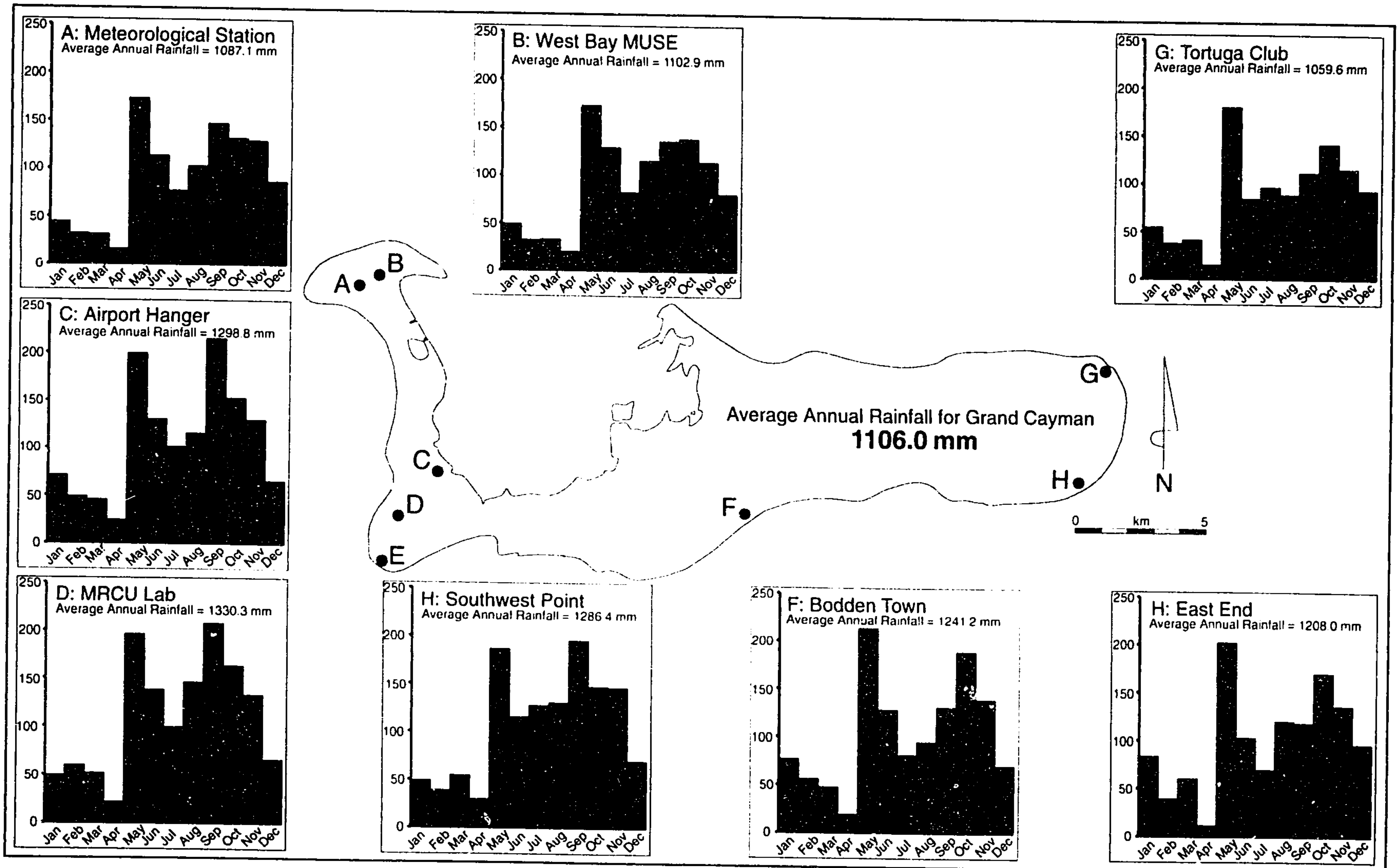


Figure 3.2: Average annual and monthly rainfall (mm) 1986 - 1993 (data collected by Natural Resources Grand Cayman).

average annual rainfalls of 1241.2 mm and 1208.0 mm, respectively, for 1986 – 1993 (data collected by Natural Resources Grand Cayman).

Island wide precipitation appears to be decreasing. Annual rainfall at the Owen Roberts International Airport between 1920 and 1965 was 1740 mm compared to 1513 mm from 1920 to 1987 (Ng *et al.*, 1992).

Tropical cyclones and hurricanes, which generally occur during the latter part of the rainy season (August–October), are responsible for immense changes in water energy. "Great Storms" originate outside the Caribbean Sea and, following the path of greatest frequency, are typically carried into the Caribbean by the Easterlies (Fig. 3.1). Clark (1988) considered all tropical storms and hurricanes that affected the Caribbean between 1886 and 1987. He showed that tropical storms pass within 100 miles of Grand Cayman at a frequency of 2.7 years, 50 miles at a frequency of 4.3 years, and over Grand Cayman at a frequency of 12.5 years. Hurricanes pass within 100 miles of Grand Cayman at a frequency of 2.5 years, 50 miles at a frequency of 3.7, and over Grand Cayman at a frequency of 9.2 years (Clark, 1988).

The history of hurricanes on Grand Cayman is extensive. One of the earliest mentioned hurricanes, in August 1785, was "so terrific in its force it tore up all but one tree at South West Point" and destroyed every house and defoliated the entire west half of the island (Williams, 1970). The low–lying land between South Sound and North Sound was completely submerged with waves crossing the island during the hurricane in October 1846. The hurricane of October 1910 passed 40 km north of island and produced waves 5 m high (Williams, 1970). Eyewitness accounts during another "Great Storm" in

1932 estimated winds at 200 mph (329 km/hr). Coral heads 0.6 to 1.5 m in diameter, originating in water less than 15 m deep, were piled into boulder ramparts on the shore (Rigby and Roberts, 1976). The last hurricane to effect Grand Cayman was "Gilbert" in September 1988. Although the eye of the storm was reported to pass over the island relatively little damage resulted.

B. HYDROLOGY

1. Tides and Storm Surges

Tides around Grand Cayman are low–amplitude, semi–diurnal with a strong diurnal component. Accurate tide measurements have been available since 1976 and are measured from the western part of South Sound and the southeastern shore of North Sound. The data from South Sound is the closest available estimate for open water tide levels near Grand Cayman. Tidal amplitude averages 25.8 cm and the maximum recorded range between high and low sea–level is 1.0 m (Table 3.1; Burton, 1994).

No major storm or hurricane surges have been measured. A tropical storm in

	South Sound (cm above datum)	North Sound (cm above datum)
Mean High Water	24.8	25.1
Mean High Water (Spring Tide)	29.1	29.1
Mean High Water (Neap Tide)	20.4	20.8
Ten Year Maximum	77.2	60.5
Mean Low Water	-1.0	-3.2
Mean Low Water (Spring Tide)	-5.0	-8.1
Mean Low Water (Neap Tide)	2.8	1.8
Ten Year Minimum	-39.1	-38.6

Table 3.1: Tide measurements from 1976 to 1985 (Burton, 1994).

September 1976 passed far to the south of Grand Cayman and caused a 77.2 cm swell. Hurricane "Allen" in August 1980 passed 90 km to the north of Grand Cayman and produced an ocean surge estimated at only 40 cm.

Grand Cayman lacks extensive shallow water areas where storms can "pile" water. Thus, Clark (1988) suggested that storm tides of 2.5 m above sea–level would be "extremely rare". Most of the island, however, is less than 3 m above sea–level and historical records of hurricanes describe "breaching" of the sea from the south coast to North Sound.

No suppression or enhancement of tides in the studied lagoons was noticed. South Sound is similar to Frank Sound in size and shape, and is the site of the primary tide gauge for Grand Cayman. The measurements from the west end of South Sound are taken to be equal or near equal to open ocean tides (Table 3.1). North Sound is far larger and more isolated from the open ocean than the studied lagoons and the average tidal amplitude is only 2.5 cm greater than South Sound (Table 3.1).

2. Waves

Primary wave energy on Grand Cayman is due to Northeast Trade Winds that have speeds from 3 – 7 m/sec during calm weather (Darbyshire *et al.*, 1976). The island is protected from high–latitude storm swells originating in the North Atlantic by Cuba and from the South Atlantic by South America and Lesser Antilles. Dominant wave approach changes seasonally with winds from the northeast during the winter months, to east and south–east during the summer months. As a result, the west facing coast is a leeward margin and all others are windward (Fig. 3.1A). Wave energy varies over two orders of magnitude between windward east coast and the leeward coast (Rigby and Roberts, 1976).

Due to variations in fetch, windward margins experience different wave regimes. Blanchon and Jones (1995) divided the coastal areas of Grand Cayman into 1) *exposed–windward margins* (south and east sides) which experience the greatest fair–weather wave energy (1.25 – 2.5 m wave height), 2) the *protected–windward margin* (the north side) which has a limited fetch and is effected by calmer seas (< 1.25 m wave height), and 3) the *leeward margin* (the west coast) where the dominate wind is offshore. Smaller–scale variations in coastal orientation also affect the wave regimes. Therefore windward margins were described as *wind–facing* if they were oriented towards the east, or *sheltered* if they have a westward orientation.

Fair–weather wave conditions are infrequently disrupted by tsunami and storm generated swells. Winter storms, with gale force winds (14 – 28 m/sec), from the north bring temporary high wave energy to the north and west coast. Hurricanes generally approach from the east have winds > 32.7 m/sec and wave heights > 15 m. Historical records describe waves passing over the entire island between South Sound and North South.

Jones and Hunter (1992) demonstrated that a severe hurricane, or a tsunami triggered by a major earthquake or slumping on nearby submarine slopes, produced severe conditions in approximately 1662 AD. The waves picked up 10 tonne blocks from the sea floor on the southern shore of Grand Cayman and moved them 15 to 18 m vertically and 50 to 60 m horizontally.

Frank Sound and Pease Bay are on the exposed–windward margin of the south coast. The adjacent ocean typically experiences moderate seas (1.25 – 2.5 wave height) with the highest wave energy occurring during spring through fall. Both lagoons, however, have a well–defined linear reef that separates the lagoon from the open ocean, and normal weather wave energy is largely broken by this barrier. Roberts (1981) showed that an energy loss of 97% takes place as a wave crosses a reef from shelf to lagoon at low tide. Less energy is lost — approximately 70% — at high tide when water depth increase over the reef. During the field study, waves in the lagoon were seldom greater than 0.50 cm in amplitude despite the fact that waves with amplitudes of more than 2.0 m were present on the open ocean side. This general pattern is disrupted in Frank Sound where a tidal channel in the middle of the reef allows the open ocean waves to enter the lagoon. Waves travel into the lagoon in an arcuate pattern emanating from the channel opening. Waves near the channel opening were typically 0.50 – 1.00 m in amplitude during the field study.

3. Currents

Three types of currents affect Frank Sound and Pease Bay; a longshore current, a strong underset current, and a tidal current. Collectively, these currents produce a general westward lagoon circulation (Fig. 3.1B).

Longshore current is poorly developed in Frank Sound and Pease Bay because most wave energy is disrupted by the reef before reaching the lagoon shores. Wind–driven waves generated in the lagoons and the remnant wave energy that crosses the reef crest generate a weak westward longshore current. Waves passing through the channel in

Frank Sound produce a slightly stronger west–southwest longshore current on the north–west shore of Frank Sound (Roberts, 1988).

The underset current is driven by the hydraulic head created when water is piled over the reef crest by waves (Suhayda and Roberts, 1977). In order to maintain equilibrium with the adjacent ocean, water must escape from the lagoon. Consequently, strong currents develop near breaks in the reef. The current over the reef crest, and out of the lagoon through channels, increases as the tide drops and decreases as tide rises. At low tide, waves are more completely broken over the reef crest converting more wave energy into shoreward current energy (Suhayda and Roberts, 1977). Lower sea–level also decreases the area water has to escape the lagoon thereby concentrating the water exiting the lagoon in channels.

Tide exchange changes the water level in the lagoons an average of 26 cm twice a day (Table 3.1). Water is added to the lagoons over the reef as the tide rises and removed through tidal channels as the tide drops.

4. Temperature

Water temperature in Hog Sty Bay, Georgetown, Grand Cayman between February 1991 and May 1994 was 26°C (January – March) – 29°C (June – October) and averaged 28°C (Hog Sty Bay Water Quality Investigation, Water Authority and Department of the Environment, Grand Cayman). The difference in temperature between the shallow waters of North Sound and the open shelf waters off of Hog Sty Bay rarely exceeds 1 °C with North Sound being slightly warmer during the summer months and slightly cooler in the winter months (Fig. 3.3A). These temperatures are based on monthly

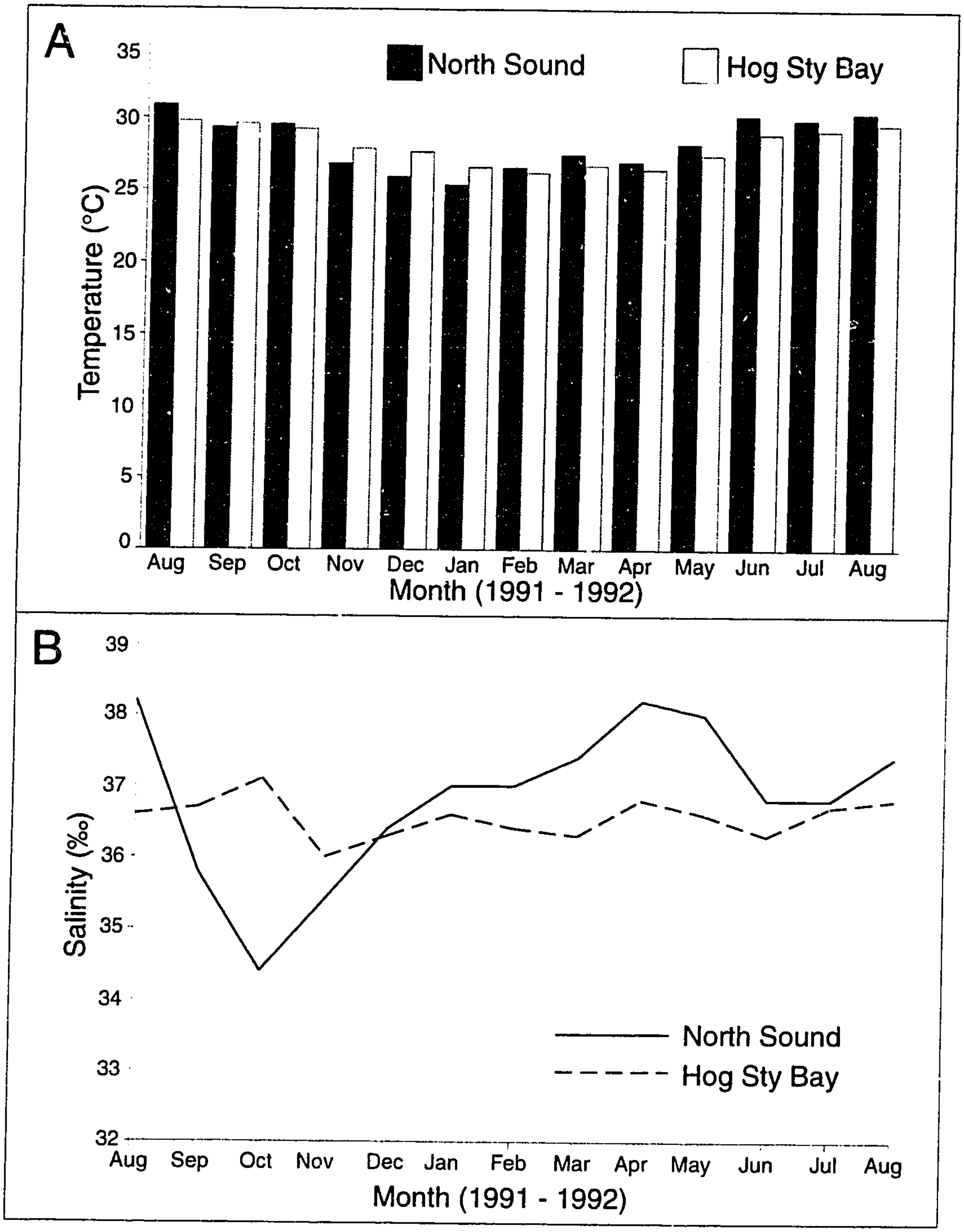


Figure 3.3: A) Water temperature and B) salinity for southeast North Sound (Water Quality Survay, Department of Environment, Aug. 1991 - Aug. 1992) and Hog Sty Bay, Georgetown (Hog Sty Bay Water Quality Investigation, Department of Environment and Water Authority, Feb. 1991 to present), between 1991 - 1992.

averages and do not show short term cooling that can rapidly occur in shallow water during storms such as Nor' Westers.

The circulation in both of the studied lagoons far surpasses the circulation in North Sound so temperatures are near that of shallow open marine such as those found in Hog Sty Bay.

5. Salinity

Salinity around Grand Cayman is 35 – 38 ‰ with a chlorinity of 19.9 – 20.9 ‰ (Moore, 1973). The average salinity in Hog Sty Bay, offshore Georgetown, between February 1991 and May 1994 was 35.4 ‰ (Hog Sty Bay Water Quality Investigation, Water Authority and Department of the Environment, Grand Cayman). Salinity measurements taken during the field study in Frank Sound, Pease Bay, and offshore Georgetown were 36.5 ‰ (Fig. 2.1).

Salinity remains relatively constant on the open shelf, between 36.0 – 37.1 ‰, while it fluctuates between 34.4 – 38.2 ‰ in southeastern North Sound (Fig. 3.3B). In North Sound the lowest salinity corresponded to the end of the rainy season and the highest salinity corresponded to the end of the dry season.

Fluctuation of salinity in Frank Sound and Pease Bay are believed to be minor. Freshwater runoff that could dilute lagoon water is minimal from a karst terrain where surface streams are rare. The land adjacent to the study area is also of relatively high relief, with the acceptation of Meagre Bay Pond, eliminating mangrove swamps as a source for fresh and brackish water and limiting the area for storm runoff. In addition to this, relatively strong wind and wave driven circulation is constantly adding normal marine water to the lagoons and preventing both dilution and evaporation from causing fluctuations from normal marine salinity.

Rigby and Roberts (1976) described belted salinity in South Sound with lower salinity found near shore, associated with run off and swamp drainage, and open–ocean salinity near the reef. Belted salinity was not found in Frank Sound or Pease Bay. Surface waters were seen to be mixing with rain waters down to 0.5 m below the surface during the heaviest rains. In less than an hour mixing patterns dissipated.

6. Turbidity

The water in Frank Sound and Pease Bay was clear at most locations. Objects were generally visible and distinguishable at 10 – 20 m in undisturbed water. Visibility was greatest near the reef crest where all fine material has been stripped away by wave energy and clear ocean water passes over the reef. Visibility was poorer near shore in the *Thalassia* grass beds where fine material trapped by the grass becomes re–suspended by wave energy. Visibility in the *Thalassia* beds near shore in Frank Sound and Pease Bay after storms decreased to < 2 m due to suspended fine material.

C. LAGOON GEOMETRY

Frank Sound and Pease Bay are located on the south–east end of the island (Fig. 1.2). Each lagoon is bound by land to the north and a barrier reef stretching from headland to headland to the south. Frank Sound has one major break in the reef that has been widened for navigation purposes. Pease Bay has no navigable breaks in the barrier reef; however, the reef crest is slightly deeper in the east end of the lagoon. Frank Sound is approximately 4 km long and has a maximum width of 1 km. Pease Bay is approximately 4 km long but has a maximum wide of 0.5 km.

1. Bathymetry

Bathymetry is controlled by bedrock topography, the amount of sediment carried into the lagoon or produced *in situ*, and ability of water to deliver or remove sediment from the lagoon during both fair–weather and storm conditions.

Water depths in Frank Sound rarely exceed 3.0 m and averaged 2.0 m below mean sea–level (Fig. 3.4 – 3.6). Water depth increases gradually, reaching 1.0 m within 100 – 150 m offshore. Most of the lagoon the floor is flat bottomed and 1.5 – 2.5 m deep, slightly shallower on the flanks and deeper in the central region. Depth gradually decreases across the back–reef to the reef crest and over 100 – 150 m changes from 1.5 – 0.5 m. The reef crest depth is 0.0 – 0.5 m and on both sides of the channel opening for approximately 0.5 km it is generally above sea–level at low tide. The only divergence from this pattern is north of the channel opening where the lagoon floor is bare rock and sediment is absent. This area tends to be deeper (> 2.5 m) and reaches 3.8 m — the maximum water depth found in Frank Sound.

Pease Bay is slightly shallower than Frank Sound, having an average water depth of 1.5 – 2.0 m (Fig. 3.4 and 3.7). Off shore, water depth increases more rapidly in central Pease Bay than in Frank Sound (0.0 – 1.5 m water depth within 30 m from shore; Fig. 3.7; transect PB–8 and PB–9). In the east and west thirds of the lagoon the shape of the shoreline prevents the removal of sediment by currents and the water deepens gradually (Fig. 3.7; transects PB–1 and PB–3). The back–reef area in Pease Bay is variable. The

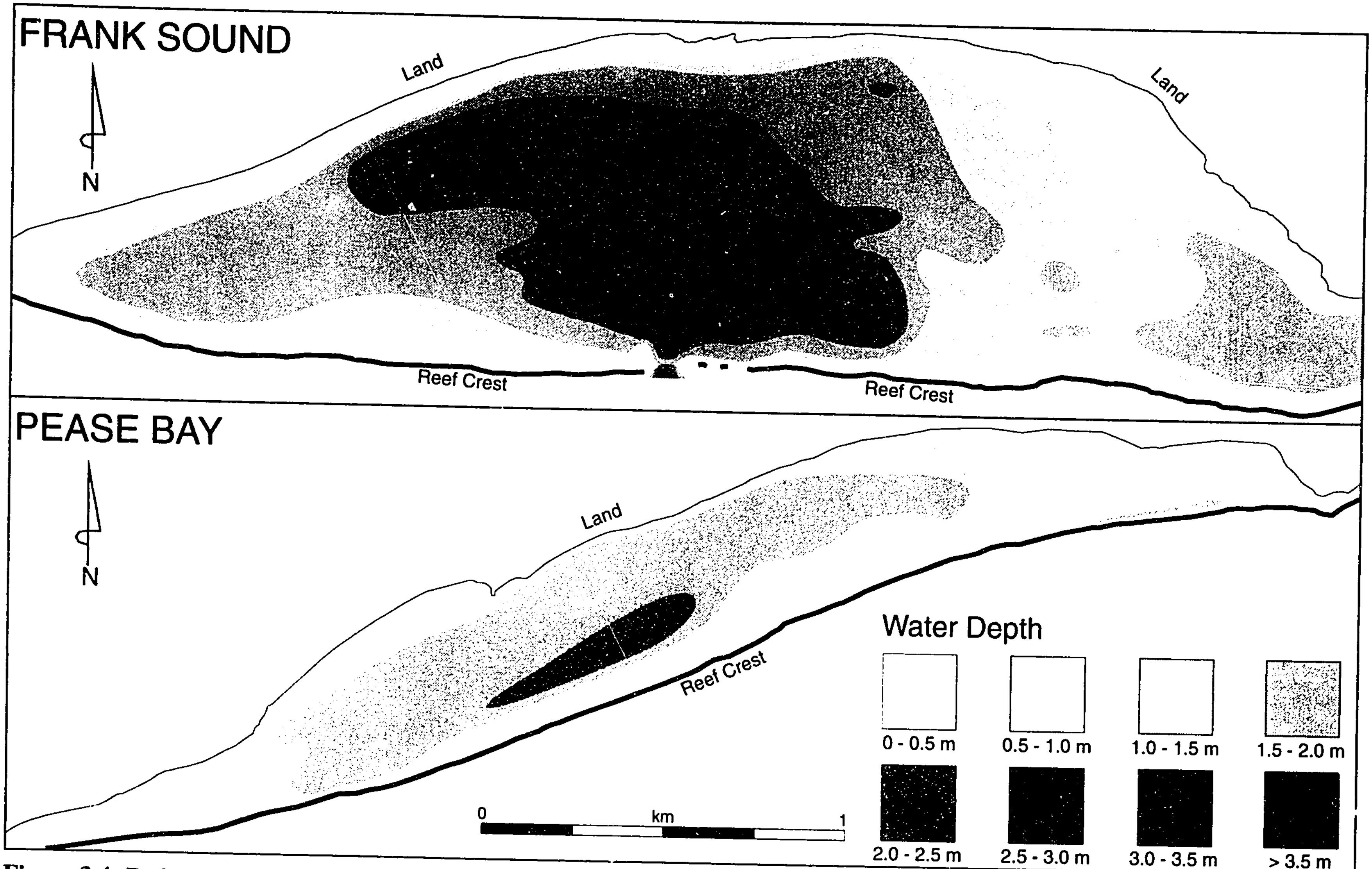


Figure 3.4: Bathymetry of Frank Sound and Pease Bay.

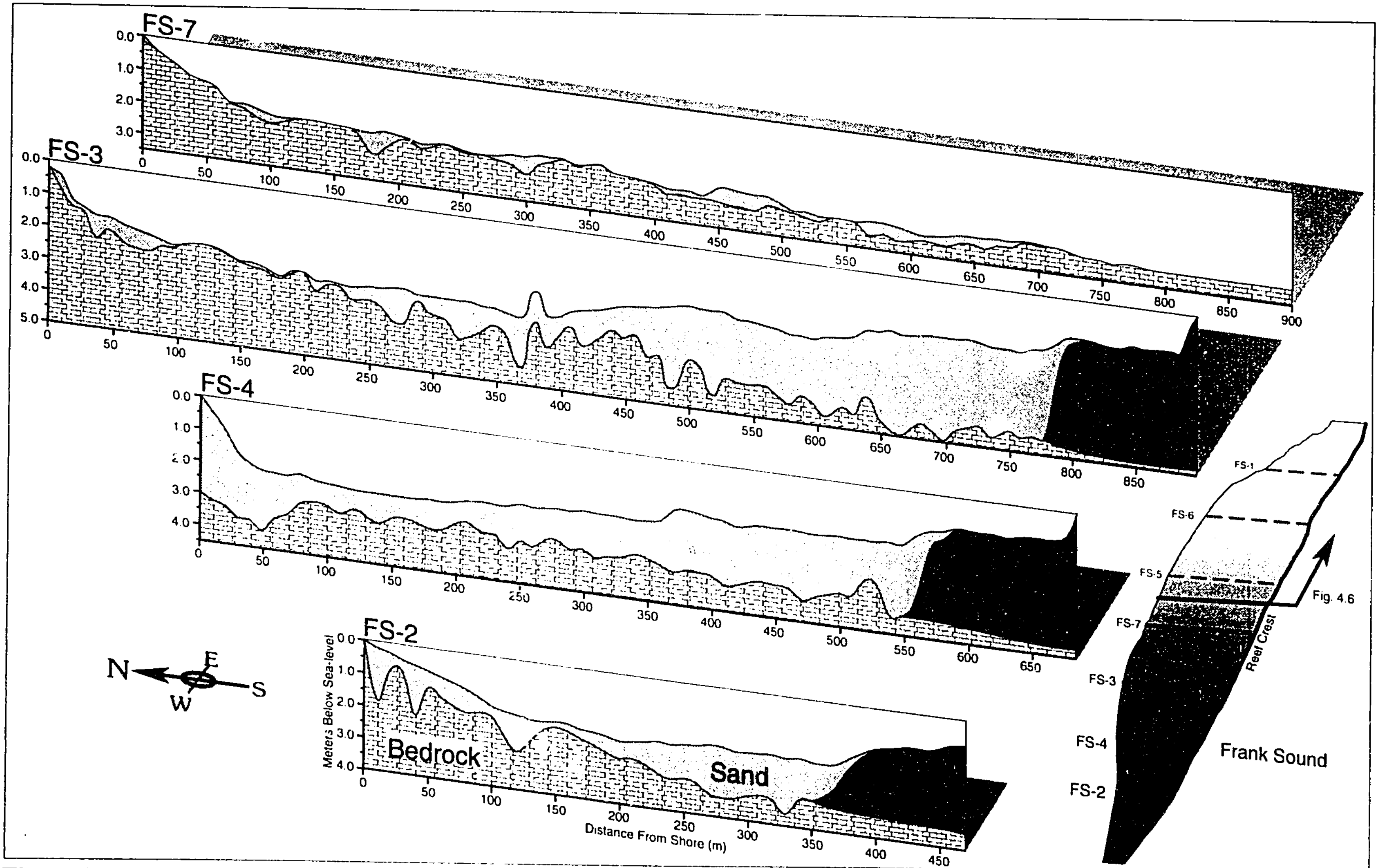


Figure 3.5: Profiles across four transects in western Frank Sound showing bathymetry, sediment thickness, and bedrock topography.

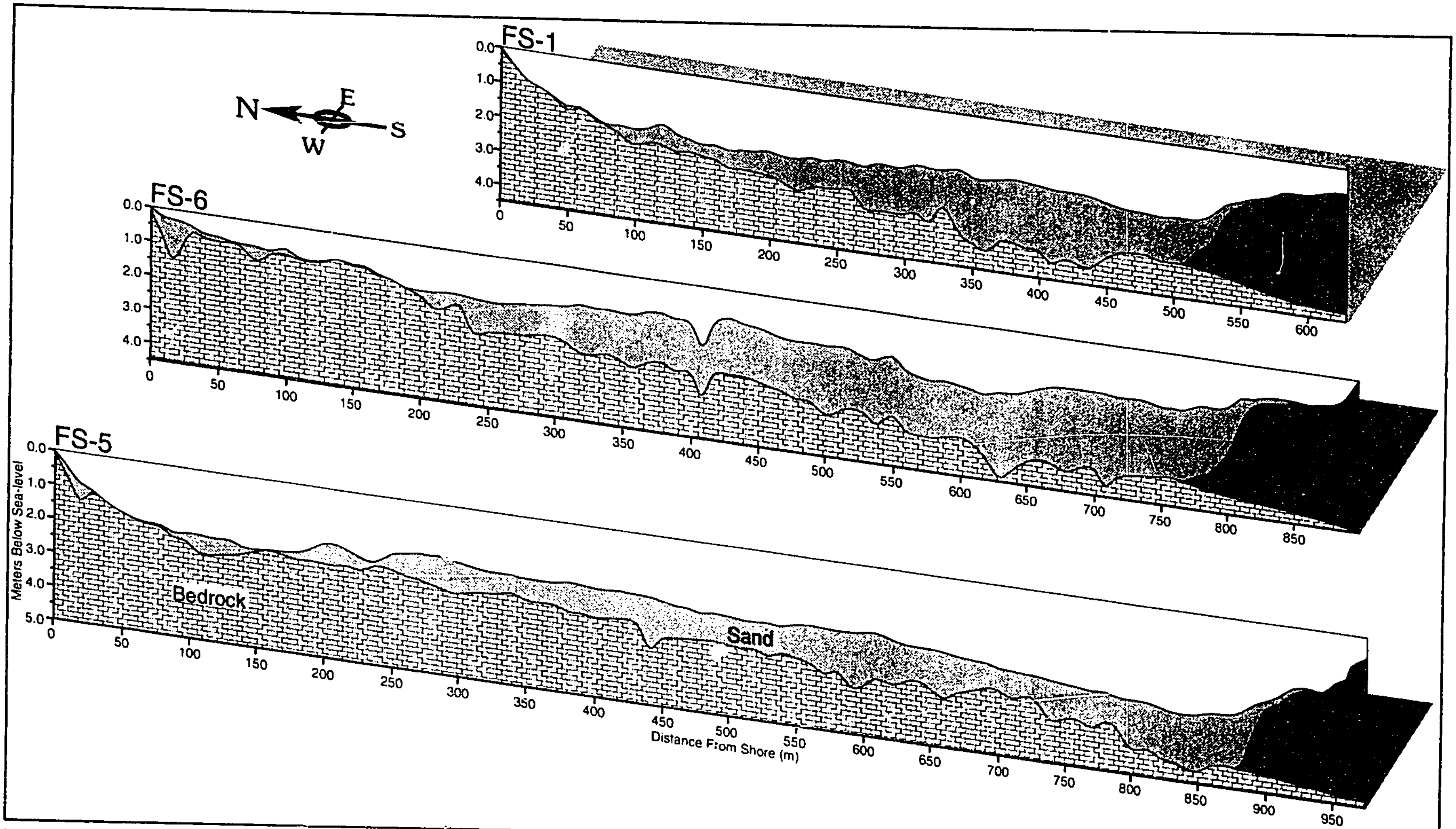


Figure 3.6: Profiles across three transects in eastern Frank Sound showing bathymetry, sediment thickness, and bedrock topography.

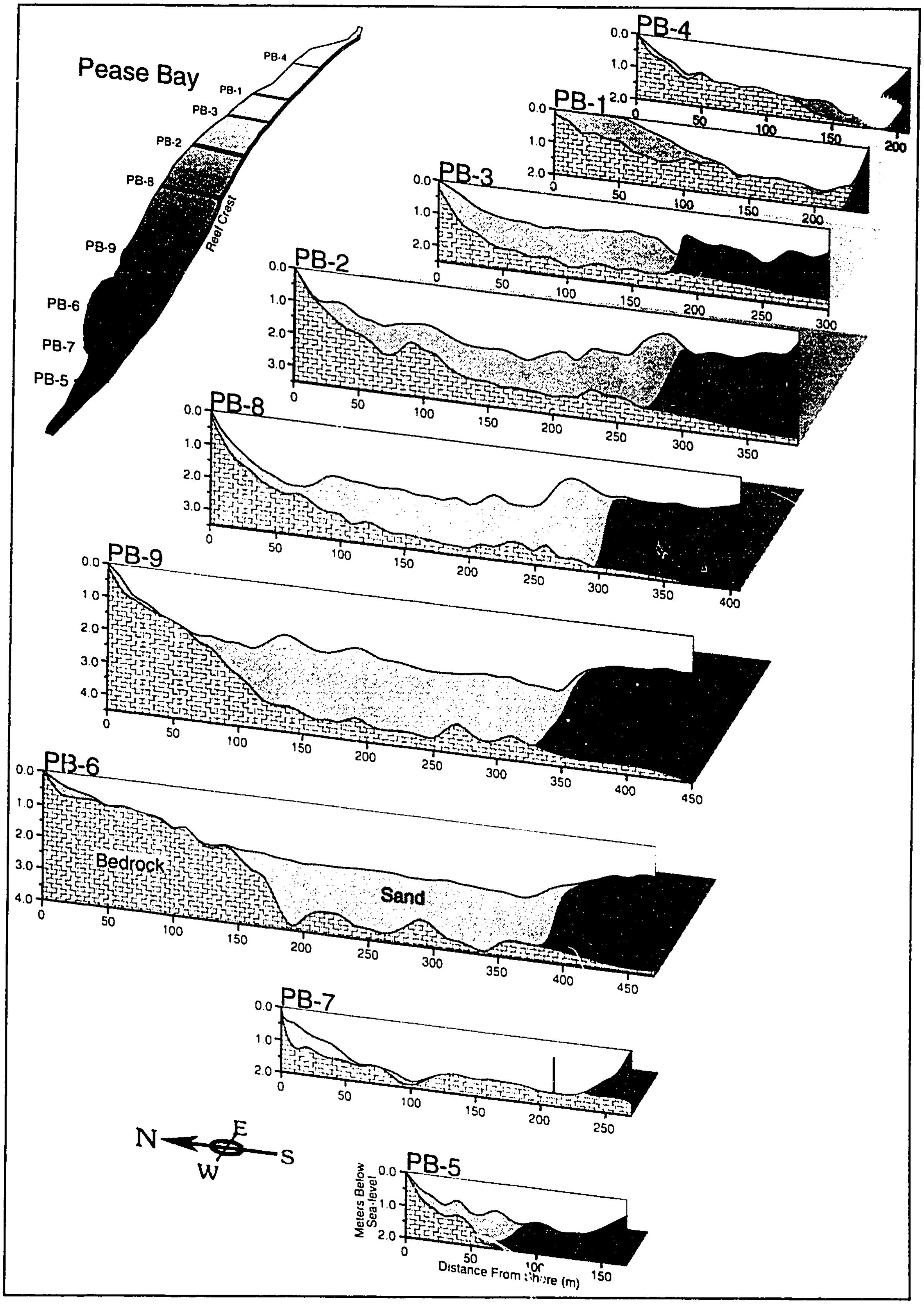


Figure 3.7: Profiles across the nine Pease Bay transects showing bathymetry, sediment thickness, and bedrock topography.

western half of the lagoon is similar to Frank Sound, having a coral rubble back–reef slope that deepens from 0.5 – 1.5 m over a distance of 30 – 80 m. In the eastern half the back–reef area has a series of shallow *Thalassia* sea grass banks (east–central) and a plateau of fused rubble (east). Over most of its length the reef crest is at or near sea–level except at the western end (Fig. 3.7; transect PB–5) and in the eastern end adjacent the rocky plateau (Fig. 3.7; transect PB–3), where it is ≈0.5 m. The deepest water depth (2.15 m) is in the central region.

In both lagoons dramatic local variation in bathymetry can occur that are not reflected in the bathymetric maps. These include blowouts, banks, and shore line undercuts in the *Thalassia* grass plains, and patch reefs in the sand plain, rocky substrate, and back–reef rubble flat areas.

Bathymetry changes dramatically and rapidly beyond the reef crest off of Frank Sound and Pease Bay (Fig. 3.8). The shelf consists of two terraces divided by the mid–shelf scarp and terminating in a near vertical shelf–edge escarpment (Rigby and Roberts, 1976). The upper–shelf terrace begins at the reef (0 m) and slopes to the mid–shelf scarp (10 m) (Rigby and Roberts, 1976; Blanchon and Jones, 1995). The mid–shelf scarp is overgrown by a reef (mid–shelf reef) of spur and groove morphology with large spurs (up to 3 m relief and 3 m across) separated by 5 m wide grooves (Blanchon and Jones, 1995). The mid–shelf reef is typically 300 m from the fringing reef crest. The lower–shelf terrace starts at the base of the mid–shelf reef (12 m) and extends to the edge of the shelf (40 m) (Blanchon and Jones, 1995) and is 250 – 300 m wide adjacent the study area. The shelf–edge is marked by reef growth and an escarpment that plunges nearly vertical to depths of

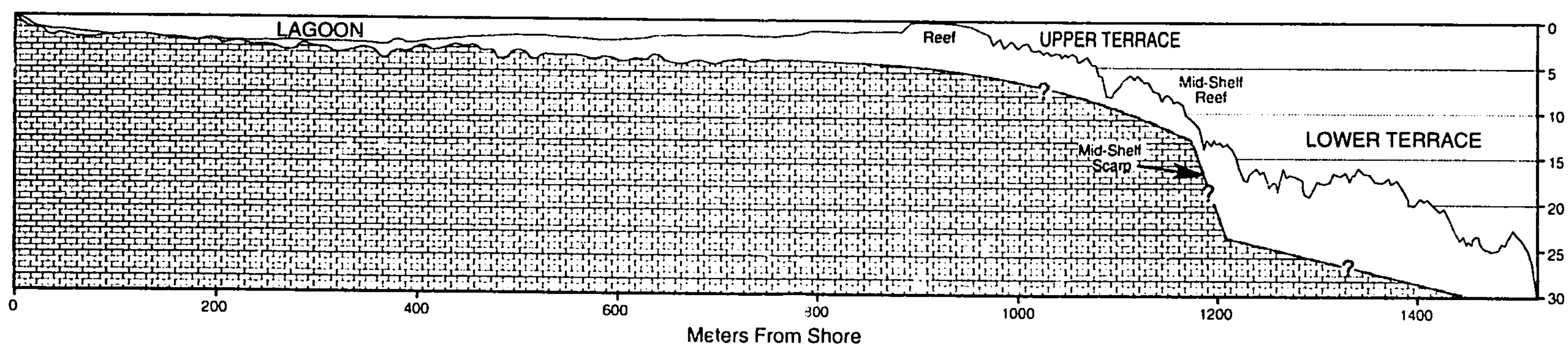


Figure 3.8: Bathymetric profile across central Frank Sound (transect FS-3) and adjacent open shelf.

115 – 145 m (Messing, 1987). From there the island slope plunges into the Cayman Trench where depths are > 7000 m.

2. Bedrock Topography

The bedrock surface appears to be small scale surface karst similar in relief to the present day Grand Cayman topography described in Jones and Smith (1988) (Fig. 3.5 – 3.7 and 3.9). The bedrock surface is uneven with many deeper 'pot–holes' on the small scale (Fig. 3.5 – 3.7) and a few larger depressions with a relief 1.5 – 2.0 m greater than the surrounding bedrock (Fig. 3.9). It is possible other large depressions exist in the lagoons that fall between the sampling transects.

In general the bedrock surface slopes to > 2.0 m below sea–level over the first 50 – 100 m from shore and then levels off. The average depth to the bedrock is 2.5 – 3.0 m in Frank Sound and 2.0 – 2.5 m in Pease Bay. The deepest measured occurrence of bedrock in Frank Sound, 4.95 m, is found in a depression northwest of the channel (Fig. 3.9 and Fig. 3.5; transect FS–3 700 m). In Pease Bay the deepest measurement is 4.2 m in center of the lagoon (Fig. 3.7).

3. Sediment Thickness

Sediment thickness is controlled primarily by bedrock topography, proximity to the sediment source, and the ability of the water to add or remove sediment from the lagoon. In Frank Sound most sediment occurs in three lobes (Fig. 3.5, 3.6, and 3.10). The two *major* sediment lobes are to the east and west of the channel opening. Thickest sediment in both lobes corresponds to depressions in the bedrock topography. The thickest sediment in Frank Sound (3.25 m) is in the western lobe in the exact location of

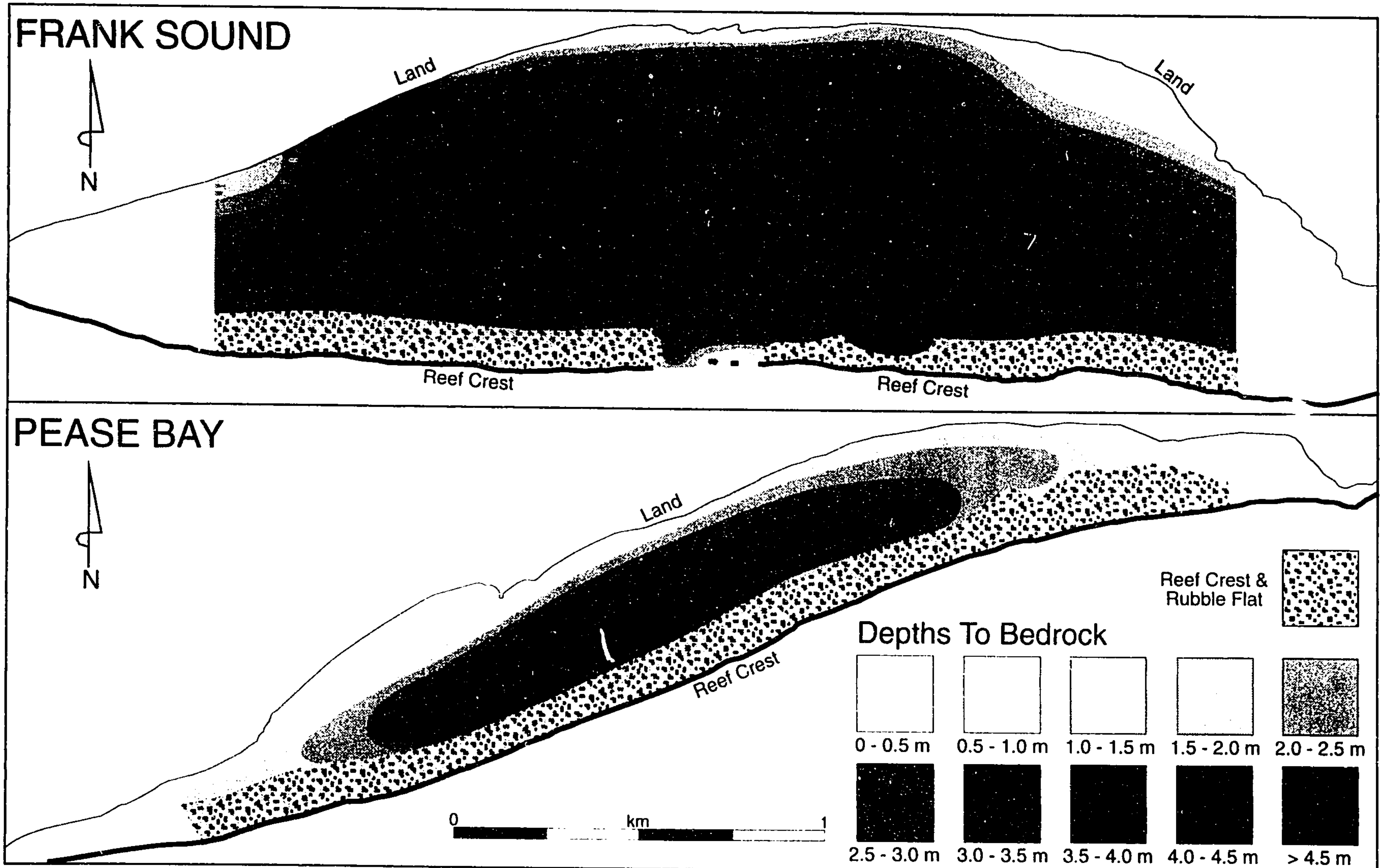


Figure 3.9: Bedrock topography of Frank Sound and Pease Bay in meters below sea level. Note the area immediately behind the reef crest is unknown.

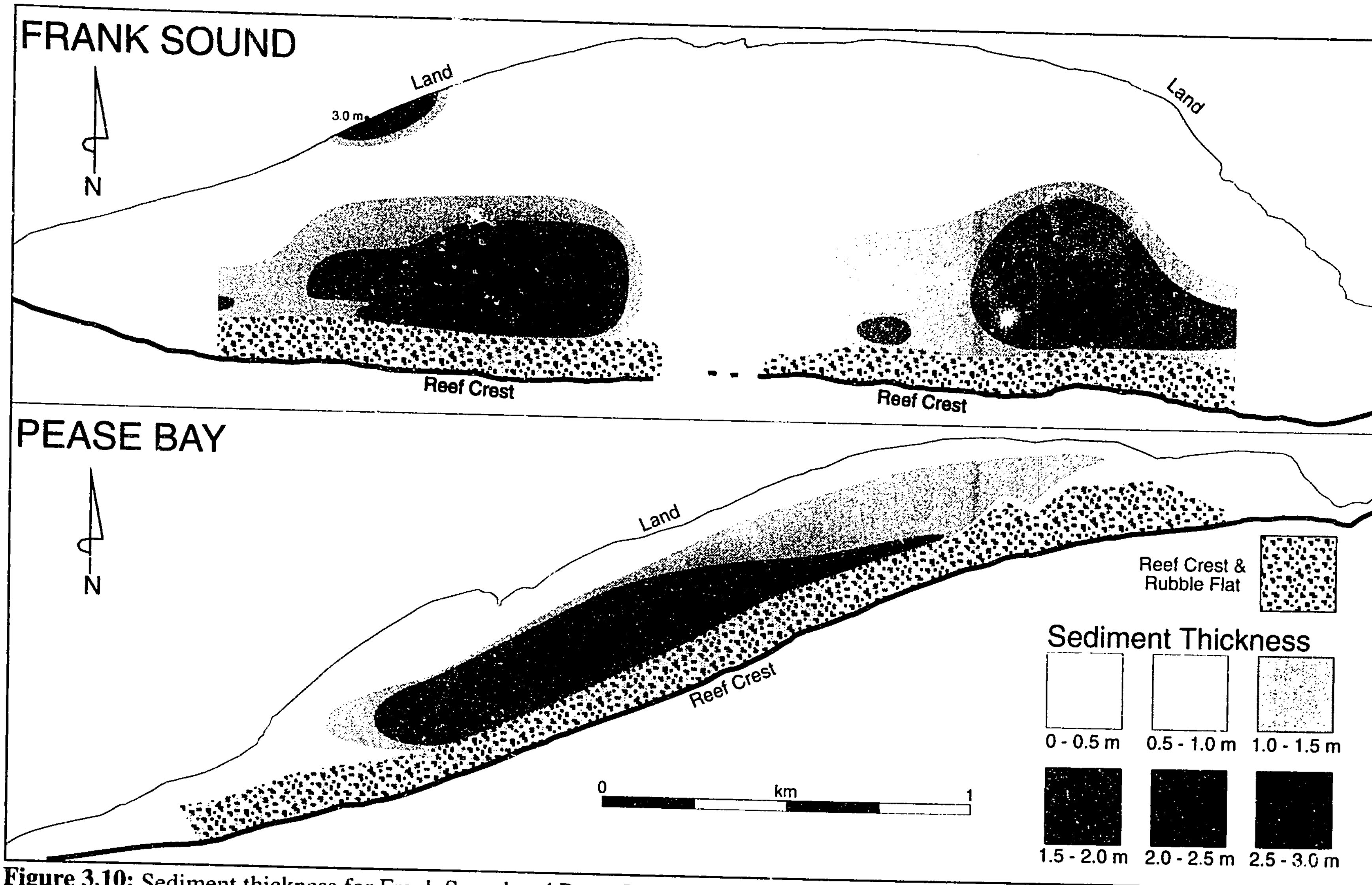


Figure 3.10: Sediment thickness for Frank Sound and Pease Bay. The area immediately behind the reef crest could not be accurately measured with the sediment probe because of boulders.

the deepest measurement of the bedrock topography. A smaller sediment lobe found near shore in western part of the lagoon (Fig. 3.10), and is the result of filling a bedrock depression (Fig. 3.4; transect FS–4 0 m). In Pease Bay average sediment thickness is ≈1.0 m (Fig. 3.10) with the thickest being (2.5 m) in the center of the lagoon beneath a local rise in the lagoon floor (Fig. 3.7; transect PB–8, 280 m).

IV. SUBSTRATE DISTRIBUTION

A. INTRODUCTION

In the study of modern carbonate sediments it is important to produce facies maps and understand the distribution and relative extent of different substrates. The production of such maps can be greatly accelerated by image analysis of aerial photographs.

In tropical areas dominated by carbonate producing organisms, water visibility is very good (horizontal visibility of ≥ 30 m in lagoons of Grand Cayman). This, combined with the shallow water depth of the study area, allows easy delineation of substrate types from aerial photographs. The study area is dominated by two visibly distinct substrates; the *Thalassia* grass plain appears dark grey to black in black and white images, whereas barren sand is light grey to white.

Aerial photographs record patterns in tones and textures that represent the objects in the imaged area (Drury, 1987, 1990; Tongpenyai, 1989; Tongpenyai and Jones, 1991). In aerial photography, a tone is a measure of the relative amount of light reflected by objects on a surface (Drury, 1987). Variation in photographic tone is determined by the characteristics of the object, geographic latitude, angle of reflected light, film sensitivity, and photographic processing. Ideally, with careful control of photography, tone is determined primarily by the characteristics of the object. Objects of different colours and different surface properties reflect light differently, and consequently record varying shades or tones in an image. Hoffer and Johannsen (1969) found that the spectral reflectance of soils and geological materials can show striking differences.

The interpretation of aerial images is based on the recognition of image properties (i.e., tone, texture, shape, size, and patterns) and relating those to real–world features (i.e., substrate, rock or soil type, vegetation cover) (Ray, 1960; Avery, 1977; Paine, 1981; Sabins, 1987; Drury, 1987, 1990). Density slicing is a simple image analysis method that converts the whole range of tones, from white to black, into a series of definable grey–scale intervals (Drury, 1990). Each interval can be defined to represent the tonal range characteristic of one type of substrate. The area occupied by each density slice of the image can then be electronically measured and the areal extent of each substrate calculated.

Density slicing is used to 1) generate a high accuracy base map of lagoon substrates for Frank Sound and Pease Bay, and 2) compare changes in the extent and location of lagoon substrates over time in Pease Bay using two sets of aerial photographs (1985 and 1992).

B. PREVIOUS STUDIES

Tongpenyai (1989) applied image analysis techniques to map shallow water lagoons around Grand Cayman. The five facies delineated were 1) the *Thalassia* grass facies, 2) a transitional zone between *Thalassia* facies and the sand facies, 3) the coral facies, 4) the brown algae facies, and 5) the sand facies.

The accuracy of the method was assessed by comparing the maps produced by Rigby and Roberts (1976) using conventional methods to the maps produced by image analysis. Using South Sound, Grand Cayman, as the test area it was found that the image analysis map was in 90% agreement with the map produced by Rigby and Roberts (1976). The results met the accuracy–level standard recommended by the U.S. Geological Survey.

C. MATERIALS AND METHODS OF STUDY

1. General

The primary images used in this study are colour aerial photographs taken in April, 1992 by Hauts–Monts Inc. The scale is 1:10,000 and falls within the range suitable for detailed mapping (Kelly and Conrad, 1969; Harris and Umbach, 1972; Hopley, 1978; Tongpenyai, 1989). Colour aerial photographs (1:50,000) taken in 1985 were used for comparison of substrates over time in Pease Bay.

The 1992 photographs of Pease Bay and Frank Sound, and 1985 photographs of Pease Bay, have good image quality and are therefore suitable for detailed image analysis. The sun was near its apex when each photograph was taken; the strong light penetrated the shallow lagoon water and provided a good image of substrates. No cloud shadows, significant water glare, or 'white caps' occurred in the imaged study area. Darkening of image tone due to water depth was not a problem because depth rarely exceeded three meters, water turbidity was low, and the substrates studied were of high enough tonal contrast to overprint the effect of water depth. Shadows and distortion caused by vertical objects were not factors due to the low relief of the lagoon floor studied. Older photographs from Frank Sound and Pease Bay, however, were not suitable for image analysis for one or more of the above reasons.

2. Digitization and Image Preparation

Image analysis was performed on digital format images created by scanning air photographs using a 24–bit colour digital scanner. Several scanners were tested and the raw scan data was compared (Fig. 4.1). The *Hewlett Packard 2c*, using *Desk Scan II v. 1.51* software (1991 – 1992), produced the maximum number of grey–levels in a test photograph and produced the most consistent data. Images scanned in 24–bit colour at 400 x 400 dpi optical resolution were stored using an uncompressed 24–bit colour Tagged Image File Format (TIFF).

Land, open ocean, white–cap waves, and areas that are present in more than one image were erased from the digital images in *Adobe Photoshop v. 2.5*. Colour images were used for this cropping because slight variations in colour permitted more accuracy than less discernible variations in tones of grey. In near–shore areas, for example, dry beach and near–shore subtidal sands were easier to differentiate in colour than on the grey–scale images. Once cropped, the images were converted to 256 grey–scale TIFF files.

All further image enhancement and image analysis was made using a shareware program called *Image v. 1.5* (Wayne Rasband) on a *Apple Macintosh IIfx*.

Digital images are made of individual 'picture elements' or *pixels* which represent a single sample of tone over an area of the sampled object. Digital image data exists as a string of *digital numbers* (DN) that represent the grey–level, or tone, of individual pixels. For this study, 0 DN represents white, 255 DN represents black, and 1 through 254 DN are tones from near–white to near–black. Image enhancement and image analysis involve the manipulation of these digital numbers.

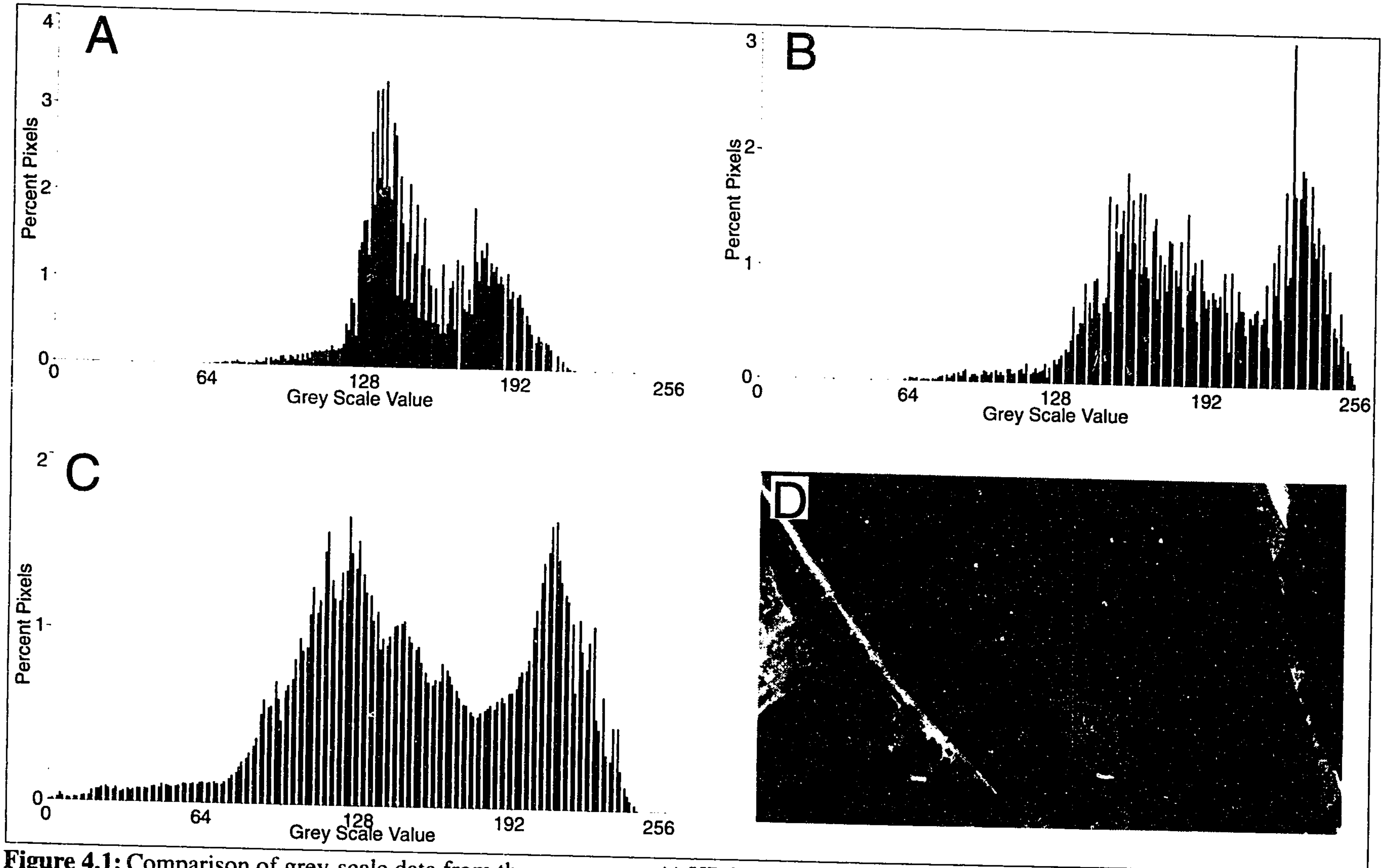


Figure 4.1: Comparison of grey-scale data from three scanners; A) HP ScanJet Plus (300 x 300 dpi optical resolution), B) Abaton Scan 300/Colour (300 x 300 dpi optical resolution), C) HP Scan Jet IIc (400 x 400 dpi optical resolution), and D) test image.

3. Image Synchronization and Enhancement

When the digital numbers of a sample area are displayed in a histogram of number of pixels versus grey–level DN, the main body of the pixels are found in a range that is narrower than 0 – 255 DN (Fig. 4.2A). This is due to the nature of the objects in the image, film sensitivity, film processing, method of photography, the image scanner, and the scanner computer software. Comparison of scanned and cropped images, for example, showed that the major boundaries in tone where not always at the same DN. The boundary between tones representative of the beach and the bare sand substrate is at 89 DN in west Pease Bay but at 37 DN in eastern Pease Bay. In order for a comparison of the images to be made the major boundaries in tone must first be made equivalent. Both contrast enhancement and image synchronization are achieved through *clipping* and *contrast stretching*.

In the sample area shown in Figure 4.2A, the main body of the image falls between 48 and 234 DN. These numbers represent the lightest typical grey–value (48 DN) in the beach area and the darkest point (234 DN) in the *Thalassia* grass beds. A small number of pixels fall above and below these *cut–off numbers* in the histograms (Fig. 4.2A). *Clipping* removes these tails in the histograms. This was accomplished by first adding, in this example, 21 DN (255 – 234 DN) to all the pixels. This shifts the histogram to the right so that the upper cut–off number is 255 DN. All pixels that were above the upper cut–off number are also set to 255 DN thus removing the upper histogram tail. The histogram is then shifted to the left by subtracting 69 DN (21 + 48 DN). This undoes the above right shift (– 21 DN) and then resets pixels of the lower tail to equal 0 DN (– 48 DN, the lower cut–off number). All the pixels in the image now fall

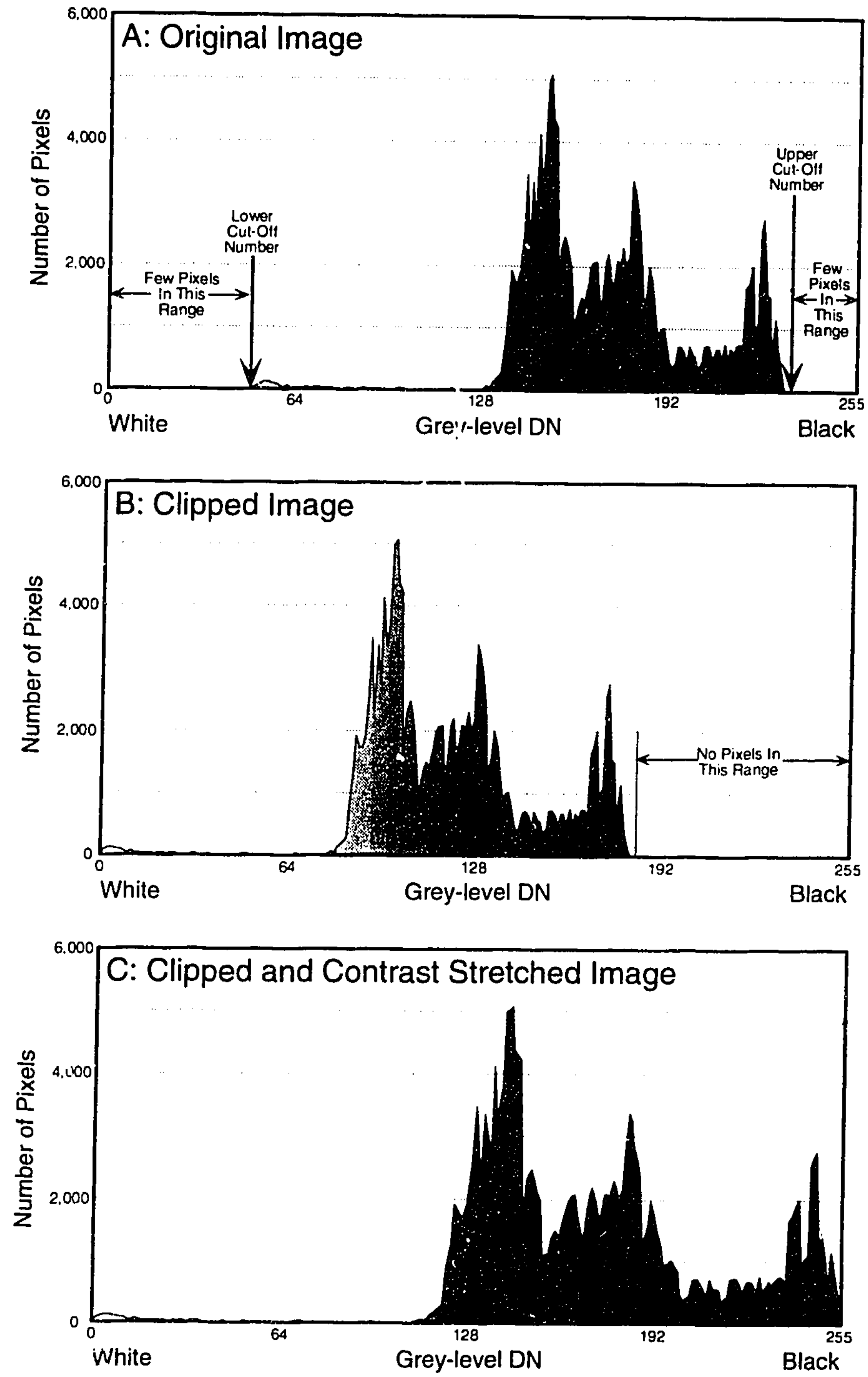


Figure 4.2: Grey-level digital number histograms showing image enhancement and synchonization procedures; A) original image, B) clipped image, and C) histogram after clipping and contrast stretching.

between 0 – 186 DN (Fig. 4.2B). Each image in this study differed in the degree of clipping required; thus the cut–off numbers were chosen manually for each.

Contrast–stretching involves setting the darkest pixel in the image equal to 255 DN (black) and the lightest pixel to 0 DN (white). All other values are stretched in a linear fashion between 0 – 255 DN to cover the whole range of brightness values (Fig. 4.2C).

The combination of clipping and contrast stretching enhances the contrast and sets the major boundaries in tone (i.e., the boundary in the tones representing major substrates) to be equal in all images (Fig. 4.3 and 4.4).

4. Density Slicing

Density slicing is the process of converting the full range of data into a series of intervals or slices, each of which express a range in the data (Drury, 1990). A density slice can be delimited to include all pixels in a tone range that represents one type of substrate. Once the density slice range is defined, the number of pixels in that slice can be calculated. Given the scale of the image (pixels per meter) the ground area of the density slice can then be derived. The pixel scale in the 1992, 1:10,000 scale suite of aerial photographs scanned at 400 dpi was ≈ 1.54 pixels/meter.

5. Classification

Classification is the process of assigning individual pixels, or ranges of pixels, to categories that are generally based on spectral characteristics of known parts of the imaged area (Drury, 1990). In this study, DN ranges were assigned to lagoon substrates by 1) carefully studying the grey–level histograms (Fig. 4.3 and 4.4), 2) inspecting the

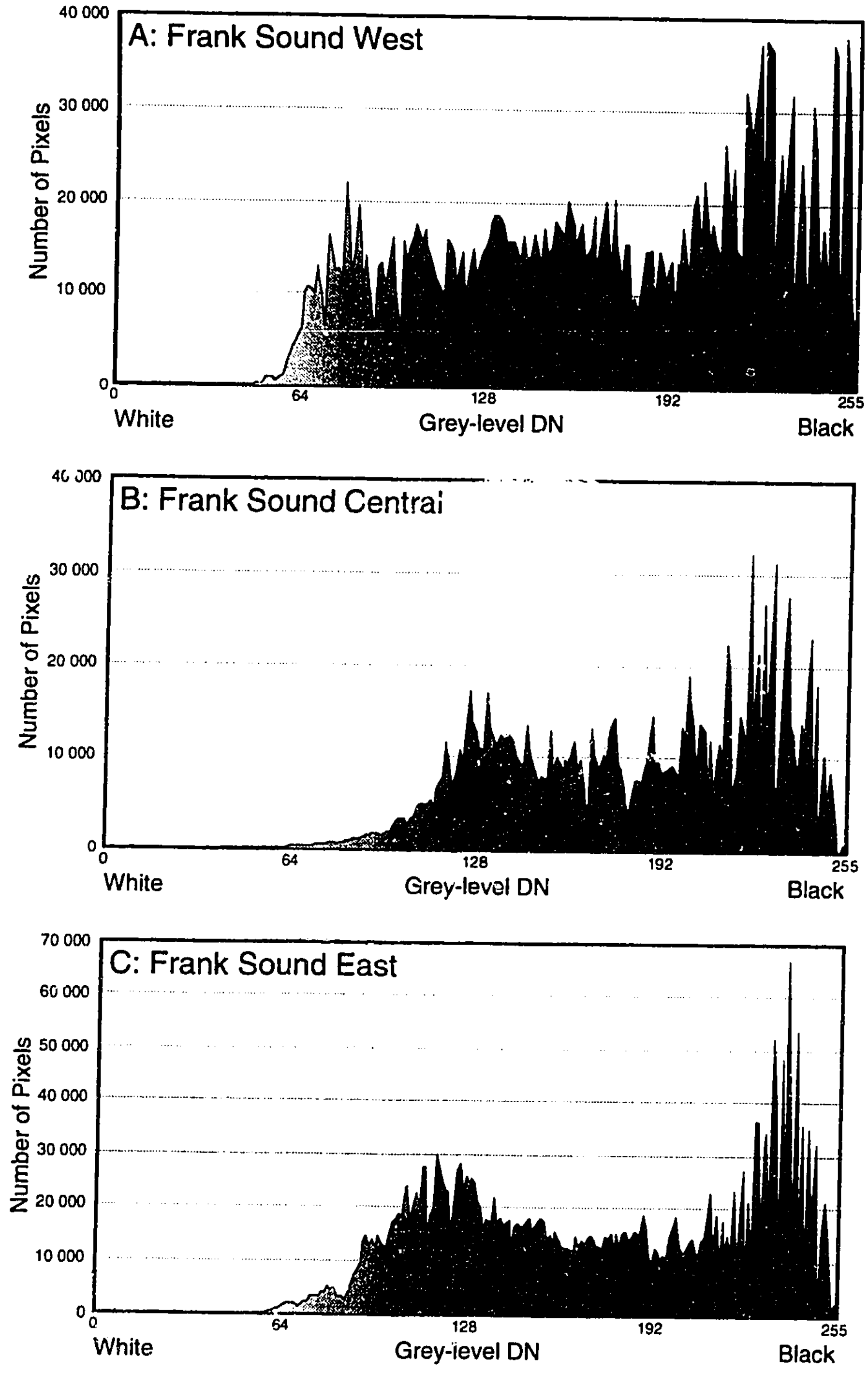


Figure 4.3: Grey-level digital number histograms for Frank Sound lagoon substrates (1992 aerial photograph suite).

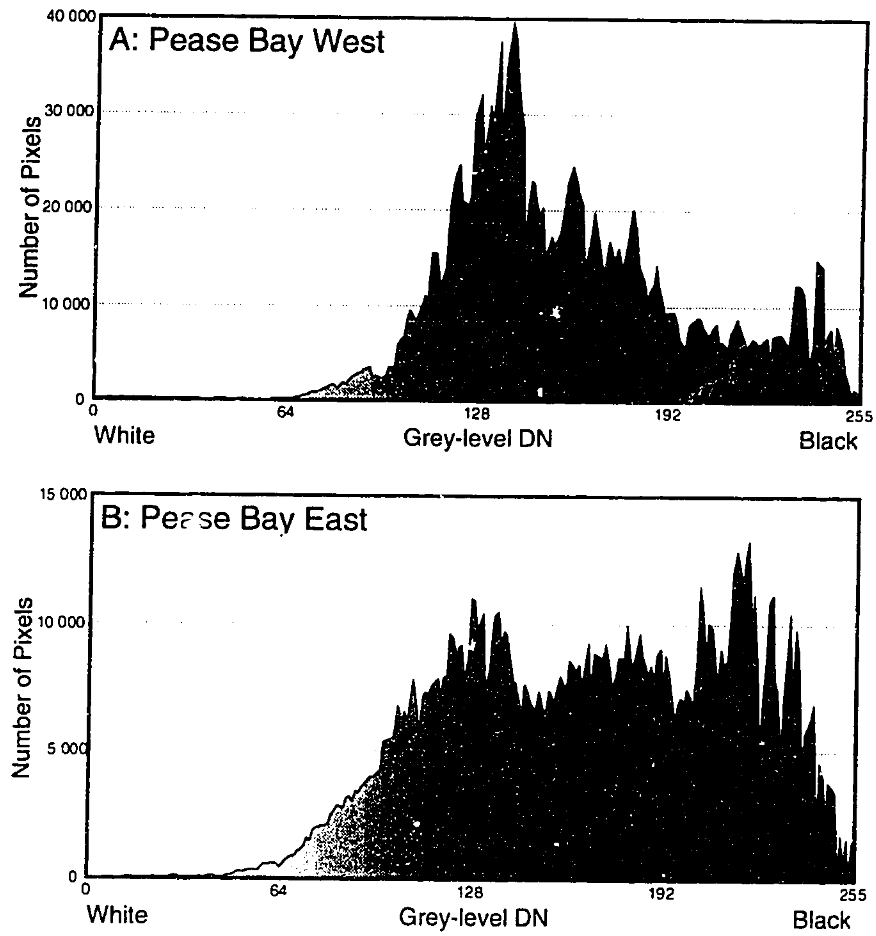


Figure 4.4: Grey-level digital number histograms for Pease Bay lagoon substrates (1992 aerial photograph suite).

digital image along the sampling transects where substrates were surveyed (Fig. 4.5), and 3) considering the spatial distribution of substrates in published maps.

The histograms show four major domains (Fig. 4.3 and 4.4); a sparsely populated region between 1–55 DN, and three major peaks at 56 – 155 DN, 156 – 205 DN and 206 – 254 DN. These are best developed in east Pease Bay (Fig. 5.4B). In some cases the first and second peaks (56 – 155 DN, 156 – 205 DN) are poorly developed and merge together (Fig. 5.3A). These four grey–level domains corresponded to the beach, bare sand, rubble and bare rock, and dense *Thalassia* sea grass substrates, respectively.

When these intervals were applied to the entire lagoons, two major problems were recognized. First, there is some overlap between most of the substrates. For example, the 'beach' substrate is 1 – 80 DN whereas the 'bare sand' is 56 – 155 DN. More complex overlaps occur between 'boulders and bare rock' and '*Thalassia* sea grass' regions in central Frank Sound. Second, a variety of substrates fall in each range. The range of 206 – 254 DN for example, was classified as '*Thalassia*'. Although most pixels in this range represent *Thalassia* beds, some pixels record gorgonian fields, coral knolls, and bare rock.

Given these problems two approaches to classification were employed.

i) Technique I

The four domains found on the histograms were classified as beach, bare sand, rubble and bare rock, and *Thalassia* plain. Each of these major categories include other minor substrates and some degree of overlap with substrates of similar tone. Most of each

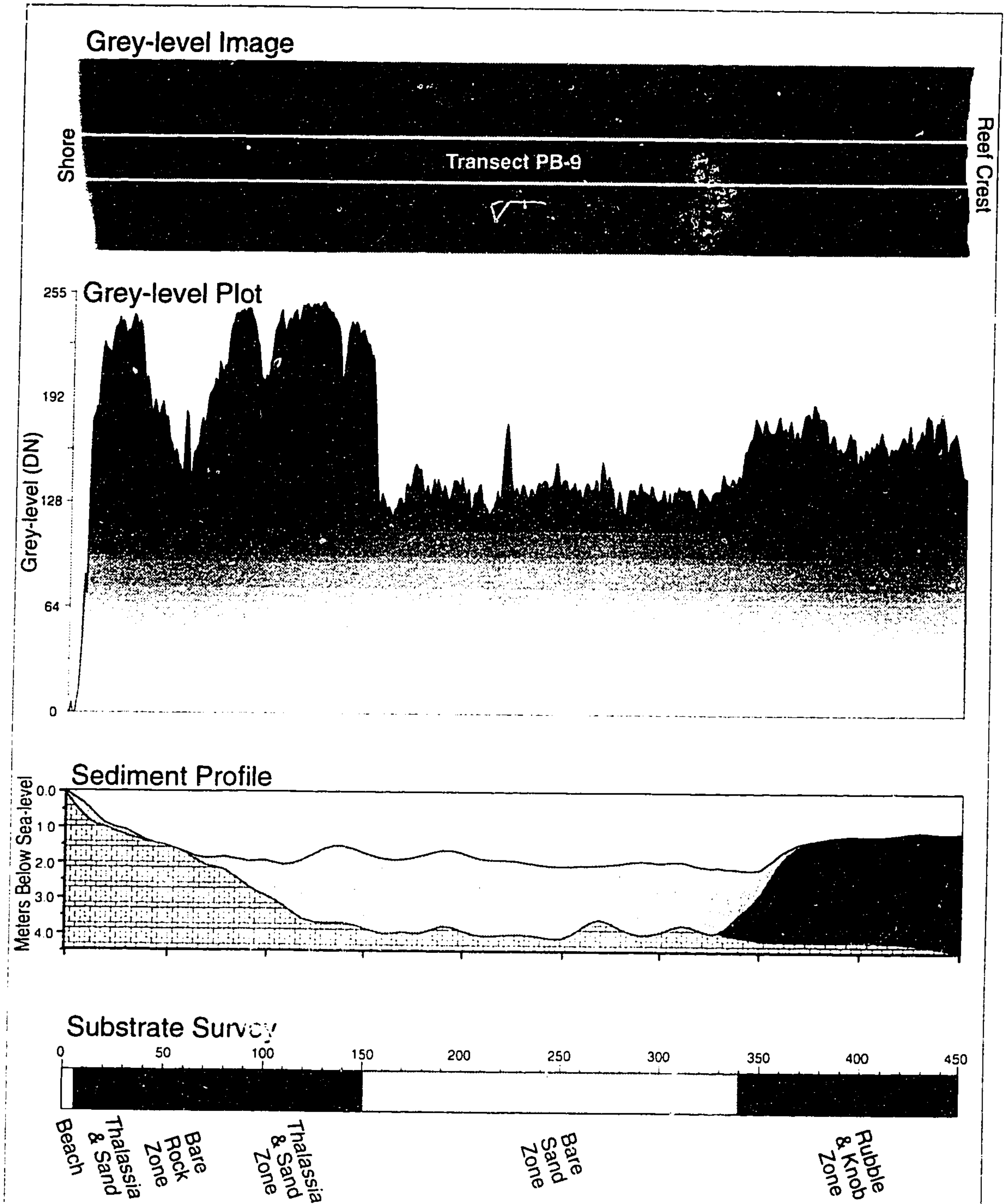


Figure 4.5: A comparison between the original image's grey-level DN along Transect PB-9, and the substrates recorded during sampling. Comparisons such as these were used in determining classification and in the calculation of error.

tone interval, however, is occupied by the main substrate (Fig. 4.5). The tone intervals given are for the 1992 aerial photograph suite.

Beach (0 – 55 DN): The brightest of the substrates, the beach, includes the wave stripped shoreline sand–strand from mean sea–level to the beginning of the offshore *Thalassia* beds. This does not include the sand that is found above mean sea–level. There is minor tonal overlap with the Bare Sand in the 56 – 80 DN range.

Bare Sand (56 – 155 DN): The first major peak represents the tonally bright *Bare Sand* substrate. It consists of skeletal debris derived from the mechanical and biological breakdown of the reef and shelf biological communities and *in situ* breakdown of various calcareous algae such as *Halimeda*. In general the sand is barren, shifting, and commonly rippled. In some areas, however, green algae such as *Halimeda, Penicillus, Avrainvillea, Udotea*, and *Caulerpa* are common and sparse populations of *Thalassia testudinum* and *Syringodium filiformi*. are present.

The Bare Sand is the most distinctive and recognizable substrate because it is largely barren and consistently bright in tone. There is, however, minor tonal overlap between the Beach and the shallow areas of the Rubble and Bare Rock substrates.

Rubble and Bare Rock (156 – 205 DN): This tonal peak corresponds to areas of bare rock and back–reef rubble. The abundant brown algae (e.g., *Padina*) in this area gives it a distinctive brown colour. The back–reef rubble area consists of sand and cobble to boulder sized pieces of coral (e.g., *Acropora palmata, Montastrea annularis, M. cavernosa*, and *Diploria strigosa*) that are loose or bound by encrusting algae.

The bare rock areas are exposed rock floor, or rock floor with a thin veneer of sand. In general the rock floor is covered with abundant brown algae along with fewer green algae and *Thalassia*. Small colonies of *Siderastrea radians*, *Favia fragum*, and *Porites spp.* are present in some areas.

Minor communities included in this tonal range are coral knolls and brown algae coated sand. Overlap is found in the transition between the Bare Sand and the *Thalassia* Plain where the *Thalassia* grass cover is greater than what is found in the sand plain but not as dense as that on the *Thalassia* Plain.

Thalassia *Plain (206 -- 2[illegible] DN):* The *Thalassia* Plain is dominated by banks of *Thalassia testudinum* and associated algae such as *Halimeda*, *Penicillus*, *Avrainvillea*, *Udotea*, *Caulerpa*, and the marine angiosperm, *Syringodium filiformi*. Minor communities included in this tone range are gorgonian fields and some coral knolls.

This broad classification technique is used to delineate temporal changes in the substrates for the following reasons. (1) The major substrates are rapidly and consistently determined. (2) Finer detail is not required because the changes involve the extent of *Thalassia*. (3) This broad classification can be derived from older photographs for which ground truthing is impossible and photograph quality is lower. (4) This technique is equivalent to the method used by Tongpenyai (1989) and Tongpenyai and Jones (1991) in their previous studies of the lagoons around Grand Cayman.

ii) Technique II

The application of technique I ignores the problems of overlapping tonal ranges and the inclusion of 'alien' substrates with the major substrates.

The problem of overlapping can be partially rectified by applying density slicing to specific areas in the image. For example, the tonal ranges representing the Beach (1 – 80 DN) and Bare Sand (56 – 155 DN) overlap. The beach, however, is confined to a narrow strip along the shore that is isolated from the Bare Sand by *Thalassia* grass. It is therefore possible to count the pixels in the 1 – 80 DN range that are shoreward of the *Thalassia* grass resulting in a more accurate measure of the Beach. Similarly, the Rubble Zone (156 – 205 DN), Bare Rock (156 – 205 DN), and Transitional Zone between *Thalassia* Plain and the Bare Sand (156 – 205 DN), all have equal tonal ranges. The Rubble Zone, however, is separated from the Bare Rock and Transitional Zone by the Bare Sand, and can be density sliced separately.

In some cases, minor 'alien' substrates can recognized and separated out from the major substrates. Coral Knolls (156 – 255 DN) are represented by a wide tonal range that overlaps with several major substrates. Their distinctive appearance and location, however, allows them to be recognized, manually removed, and measured separately.

Selective density slicing allowed the distinction between Beach (0 – 80 DN), Bare Sand (56 – 155 DN), Rubble Zone (156 – 205 DN), Transition Zone and Bare Rock (156 – 205 DN), Coral Knolls (156 – 254 DN), and *Thalassia* Plain (206 – 254 DN). Except for Coral Knolls and Transitional Zone, these substrates are described in the previous section.

Coral Knolls (156 – 254 DN): Coral Knolls are small localized communities found on the Bare Sand, Rubble Zone, Bare Rock and rarely on the *Thalassia* Plain. Colonies of one or more types of coral (e.g., *Montastrea annularis*, *Siderastrea siderea*, *Diploria strigosa*, *Acropora palmata*, *Porites porites*, *P. astreoides*) make a frame work on which gorgonians, sponge, hydrocorals (e.g., *Millepora complanata*), green algae (e.g., *Halimeda tuna*), brown algae (e.g., *Padina*), coralline red algae, and a variety of mollusks populate. The Coral Knoll substrate produces a broad tonal range because of the variety of elements present. In the aerial photographs coral knolls appear as circular or elongate oval areas that tend to be darker than the surrounding substrate. Some larger coral knolls have an aureole consisting of a dark ring of coral, gorgonians, sponge, and algae surrounding a central area, on the top of the knoll, of damaged or dead coral infested with brown algae. In some cases, especially in the *Thalassia* Plain, an additional halo of bright barren sand surrounds the knoll. Coral Knolls found in Pease Bay are too small to accurately measured using this method but in Frank Sound they are larger (> 3 m in diameter) and more readily classified. The resulting measures for Coral Knolls in Frank Sound, however, should be regarded as a minimum.

Transitional Zone (156 – 205 DN): The transition between the dense *Thalassia* cover of the *Thalassia* Plain and the sparse cover of the Bare Sand has a tonal range similar to that of the Rubble Zone. The Rubble Zone and Transitional Zone are separated in most areas by Bare Sand and can therefore be counted separately. Pixels shoreward of the Bare Sand within the grey–level range of 156 – 205 DN are classified as Transitional Zone and Bare Rock whereas those seaward of the Bare Sand they are classified as Rubble Zone.

Technique II has some drawbacks. (1) This method is largely manual in nature and therefore is time consuming and somewhat subjective. (2) The study area must be well known for the operator to select various features. (3) The resolution, scale, and general photograph quality must be sufficient to allow detailed work. In this study only the 1992 aerial photograph suite was adequate. Consequently, this technique was only used for detailed substrate delineation in the 1992 photograph suite.

6. Assessment of Accuracy

The accuracy of density slicing applied to detecting substrates in shallow water lagoons around Grand Cayman was accessed by Tongpenyai (1989) and Tongpenyai and Jones (1991). Although the hardware used for image analysis has moved from a light table and video camera system to a fully digital computer, scanner, and software system, the method remains essentially unchanged. The accuracy of this study is therefore expected to equal or surpass the previous study.

Tongpenyai (1989) and Tongpenyai and Jones (1991) compared the sample points from their maps to maps produced by conventional methods by Rigby and Roberts (1976). They compared the substrates determined from density slicing to those identified on the published map for 251 points from a 60 x 60 m grid in East Sound (north), Grand Cayman. From this, the overall map accuracy was determined to be 90% (i.e., 24 out of 251 points were misclassified). This overall map accuracy falls within the limit of permissible error rate in image interpretations recommended by the U.S. Geological Survey Circular 671 (Anderson, 1971; Anderson *et al.*, 1972).

D. RESULTS

1. Changes in lagoon substrate from 1985 – 1992: Technique I

The general trend observed by Tongpenyai (1989) and Tongpenyai and Jones (1991), of an increase in the area covered by *Thalassia* at the expense of the Sand Plain continues (Table 4.1). Unfortunately, a comparison of the area covered by *Thalassia* in Pease Bay over a longer period of time is not feasible due to the lack of suitable aerial photographs. Some comparisons, however, are possible with the changes observed in a neighbouring lagoon, South Sound, Grand Cayman. The rate of increase in *Thalassia* cover between 1979 and 1985 in South Sound was + 6.1% of the area of the lagoon (Tongpenyai and Jones, 1991). In Pease Bay between 1985 and 1992 *Thalassia* cover increased by + 5.0% of the area of the lagoon. The rates of increase in *Thalassia* cover are + 1.0% and + 0.7% of the area of the lagoons per year, respectively. Expressed as area, the *Thalassia* Plain in Pease Bay is expanding at an average rate of 8,000 m^2/year between 1985 – 1992.

Given the above rate, *Thalassia* grass will completely overgrow the Bare Sand in ~ 70 years. Since the *Thalassia* grass has had ample time to spread across the lagoon this suggest the growth is restricted or periodically driven back. Hurricanes are a likely

Pease Bay	1985 (Total Area = 1,150,943 m^2)			1992 (Total Area = 1,154,588 m^2)			
Classification	DN	Area (m^2)	% Area	DN	Area (m^2)	% Area	% Change
Beach	1 - 25	9,220	0.8	1 - 55	5,884	0.5	- 0.3
Bare Sand	26 - 105	601,015	52.2	56 - 155	537,731	46.6	- 5.6
Rubble/Rock	106 - 170	273,852	23.8	156 - 205	285,132	24.7	+ 0.9
Thalassia Plain	171 - 255	266,856	23.2	206 - 255	325,841	28.2	+ 5.0

Table 4.1: Summary of the areal extent of the major substrates in Pease Bay and the percentage change in area since 1985.

limiting force. Flood and Jell (1977) noted the effect of cyclone David had on a small shallow water lagoon on the Great Barrier Reef. Storm waves reworked lagoon sediment, winnowing out the fines (≤ 0.125 mm), while at the same time importing coarse sediments (≥ 2.00 mm). Hurricane action could rip up and/or bury *Thalassia* grass thereby limiting the colonization of the lagoons.

The increase in *Thalassia* cover is taking place near shore where sparsely populated areas in the *Thalassia* and Sand Zone are being filled in, and through a seaward migration of the boundary between the *Thalassia* and Sand Zone and Bare Sand Zone (Fig. 4.6). The Rubble and Barren Rock substrate is stable in size and distribution.

2. Distribution and extent of lagoon substrates in 1992: Technique II

The areal extent of each major substrate was determined from the 1992 aerial photographs because they best reflect the distribution of those substrates at the time of this study (Table 4.2 and 4.3). The configuration and relative distribution of the substrates shows a pattern of many lagoon settings (Fig. 4.7). Immediately behind the reef crest is a narrow and parallel band of rubble thrown back from the reef, followed by the bare sand,

Classification		West Frank Sound Total Area = 928,513 m²		Central Frank Sound Total Area = 814,386 m²		East Frank Sound Total Area = 963,846 m²		**Total Frank Sound Total Area = 2,706,745 m²**	
Class	DN	Area (m²)	% Area	Area (m²)	% Area	Area (m²)	% Area	**Area (m²)**	**% Area**
Beach	0 - 80	4,130	0.4	2.223	0.3	2,221	0.2	**8,574**	**0.3**
Bare Sand	55 - 155	388,124	41.8	338,127	41.5	487,244	50.6	**1,213,495**	**44.8**
Trans/Rock	156 - 205	160,040	17.2	180,022	22.1	127,656	13.2	**467,718**	**17.3**
Rubble Zone	156 - 205	50,722	5.5	32,209	4.0	46,794	4.9	**129,725**	**4.8**
Coral Knoll	156 - 255	7,619	0.8	19,852	2.4	480	0.0005	**27,951**	**1.0**
Thalassia Plain	206 - 255	317,878	34.3	241,953	29.7	299,451	31.7	**859,282**	**31.8**

Table 4.2: Areal extent of substrates in Frank Sound in April 1992.

Figure 4.6: A comparison of lagoonal substrates in Pease Bay in 1985 and 1992. Note the expansion of Thalassia (green) at the expense of bare sand (yellow). Rubble and bare rock is shown in shades of brown.

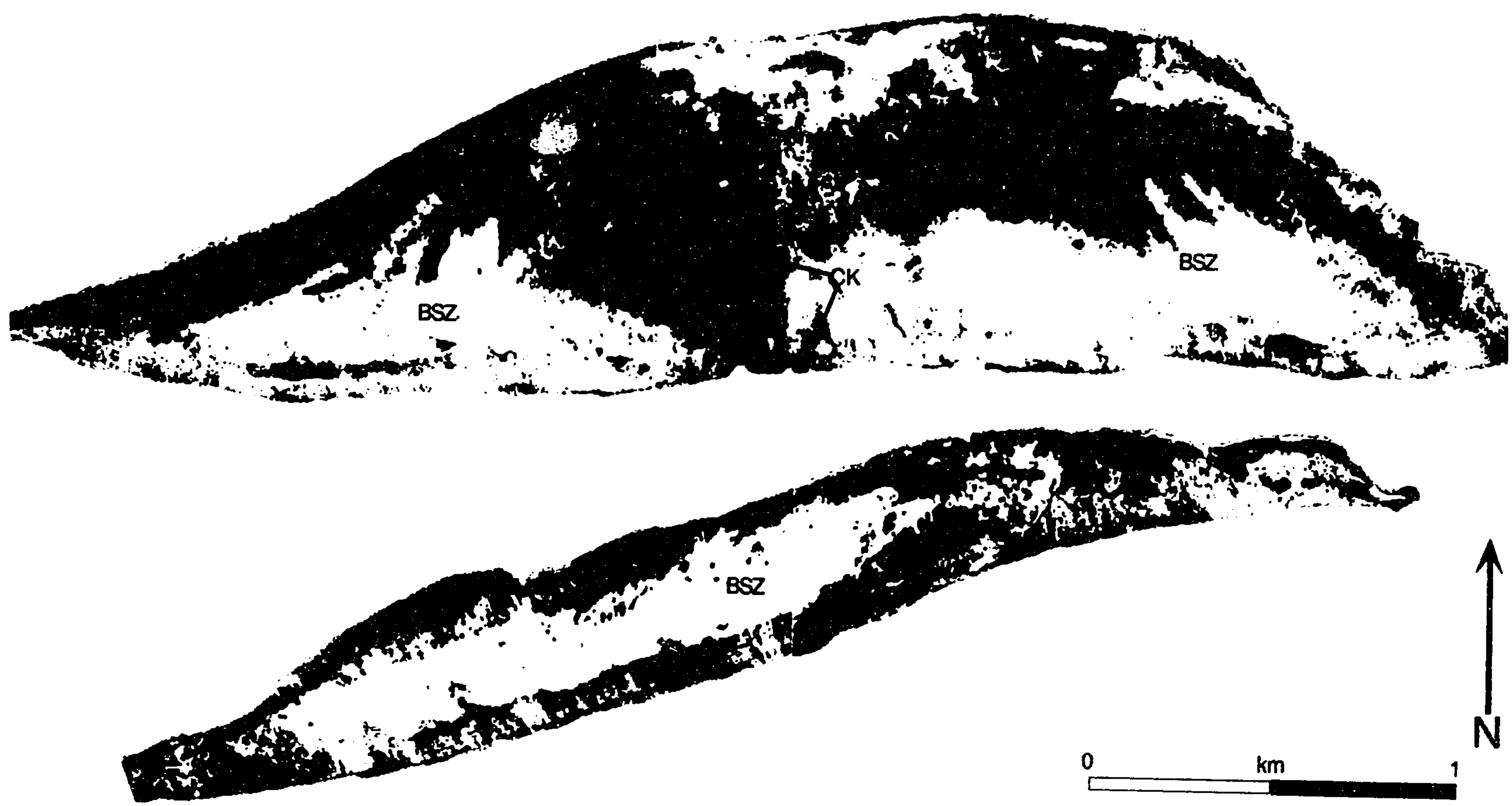


Figure 4.7: Lagoon substrates delineated using technique 2 and the 1992 aerial photograph suite. The typical sucession is *Thalassia* & Sand Zone (TSZ), Transitional Zone (TZ), Bare Sand Zone (BSZ), and Rubble & Knob Zone (RKZ), from shore to reef crest. Also shown are Coral Knolls (CK), and Bare Rock Zone (BRZ).

and near–shore *Thalassia* Plain (Fig. 4.7). There are three areas, however, where this general pattern is disrupted.

(1) In east Pease Bay, the reef crest has not developed as high as in the rest of the lagoon (0.8 – 1.0 m compared to 0.0 – 0.8 m; Fig. 3.7. Transect PB–3). This allows a strong current to sweep into eastern Pease Bay (Fig. 3.1B). This break in the reef crest is located opposite the narrowest part of the shelf adjacent Pease Bay. As a result, the back–reef rubble is characterized by a series of "spurs" extending into the lagoon nearly twice as far as the rubble in western Pease Bay. The rubble is well consolidated and locally appears to be bare bedrock. Coral, gorgonians, abundant brown algae, and clean stripped sand patches give the area a mixed and patchy tone on the aerial photographs that results in misclassification in image analysis. Adjacent and directly down current from the rubble spurs is a large *Thalassia* bank with +1.0 m relief above the neighbouring Sand Plain.

(2) In central Frank Sound the Bare Sand substrate is absent adjacent to the navigational channel. The lagoon floor from the reef crest to shore is a patchy mix of *Thalassia* Plain, Transitional Zone, and bare rock substrates. The patchy appearance reflects the

Classification		West Pease Bay Total Area = 682,036 m^2		East Pease Bay Total Area = 472,548 m^2		**Total Pease Bay Total Area = 1,154,584 m^2**	
Class	DN Range	Area (m^2)	% Area	Area (m^2)	% Area	**Area (m^2)**	**% Area**
Beach	0 - 80	4,816	0.7	3,705	0.8	**8,521**	**0.7**
Bare Sand	55 - 155	364,706	53.5	191,031	40.4	**555,737**	**48.1**
Rubble Zone	156 - 205	137,133	20.1	82,239	17.4	**219,372**	**19.0**
Trans/Rock	156 - 205	73,866	10.8	69,079	14.6	**142,945**	**12.4**
Coral Knoll	156 - 255	n/a	n/a	n/a	n/a	**n/a**	**n/a**
Thalassia Plain	206 - 255	101,515	14.9	126,494	26.8	**228,009**	**19.8**

Table 4.3: Areal extent of substrates in Pease Bay in April 1992.

areas of thin sediment cover, generally corresponding to bedrock depressions, that are colonized by *Thalassia*, alternating with barren rock (Fig. 3.5; Transect FS–7). Fine sediment and organic debris coat the *Thalassia* blades in near–shore central Frank Sound, resulting in a dull brown appearance on the colour aerial photographs and a lighter tone in the grey–scale images. This area also contains most of the large Coral Knolls found in Frank Sound.

(3) Where the reef crest converges with the shore on the flanks of Frank Sound and Pease Bay the Sand Plain is absent and barren rock substrate dominates. Associated with the barren rock are numerous small Coral Knolls and gorgonians. *Thalassia* banks are found near shore.

E. SYNOPSIS: SUBSTRATE DISTRIBUTION

Frank Sound and Pease Bay are dominated by three substrates; the back–reef Rubble Zone, the Bare Sand, and the *Thalassia* Plain. This distribution pattern is typical of many lagoon settings.

There are three exceptions from the typical pattern. (1) The Rubble Zone is twice as wide in east Pease Bay corresponding to a narrower shelf and lower reef crest. (2) North of the Frank Sound navigational channel the Rubble Zone and the Bare Sand substrates are absent: *Thalassia* grass and bare rock dominate. (3) The extreme east and west lagoon flanks are dominated by back–reef rubble followed by *Thalassia* grass or bare rock. The Bare Sand substrate is absent.

Thalassia grass substrate is expanding at the expense of the Bare Sand substrate at an average rate of 8,000 m^2/year between 1985 – 1992 in Pease Bay. At this rate the

Thalassia grass should completely overgrow the Bare Sand in ~ 70 years. *Thalassia* colonization therefore, must be limited by a natural force that counters the rapid expansion of the plant. Hurricanes are a likely limiting force.

V. SEDIMENTOLOGY AND BIOLOGICAL COMMUNITIES OF FRANK SOUND AND PEASE BAY

A. INTRODUCTION

Grain–size analysis was initially developed to describe the interaction of sediments with some physical process or agent of deposition in siliciclastic depositional environments. This application was largely successful because silicate grains are reasonably close in density, approximate a spherical shape, and the initial materials supplied to the transporting agent are random grain–sizes. For carbonate sediments, however, none of these conditions necessarily hold true. Carbonate sediment is largely biogenic in origin and is produced by a wide variety of organisms. Density and grain–shape, therefore, vary due to differences in the skeletal structure. Furthermore, grain–size is controlled by the tendency of carbonate skeletons to breakdown into structurally controlled size classes. This produces a very non–random initial size distribution.

Grain–size analysis of carbonate sediments, however, can be useful because sedimentation in carbonate environments is controlled by interaction between biological *and* physical processes. Consequently size distribution can be useful in distinguishing the relative importance of each process. For example, size distribution will have a distinct signature if biological production is high relative to the physical energy; a polymodal distribution with modes corresponding to the main breakdown sizes of the dominant skeletal material. Conversely, if water energy greatly over–shadows the biological production, a more 'siliciclastic' style Gaussian grain–size distribution will result. Sediments of Frank Sound and Pease Bay are an excellent illustrations of bioclastic sediments that have been influenced by a strong physical process.

The lagoons have been divided into three main areas based on prominent organisms and grain–size: 1) Rubble and Knob Zone (RKZ), 2) Bare Sand Zone (BSZ), and the 3) *Thalassia* and Sand Zone (TSZ). Three additional minor environments are recognized; 4) Bare Rock Zone (BRZ), 5) Coral Knolls, and 6) Shoreline substrates (Fig. 5.1).

B. MAJOR LAGOON SUBSTRATES

1. Rubble and Knob Zone (RKZ)

i) General

The Rubble and Knob Zone is an 80 – 120 m wide belt of gently shoreward sloping coral rubble immediately behind the reef crest, that serves as a buffer zone between the high energy ocean and the quiet lagoons (Fig. 5.1 and 5.2; Plate 5.1A). Fair–weather wave energy, broken on the reef crest, is converted into a shoreward moving current that sweeps over the Rubble and Knob Zone. The first 20 – 40 m into the lagoon is characterized by turbulence from broken waves and a strong oscillating current with net lagoonward movement. The rest of the zone is characterized by a moderate to strong current shifting direction from lagoonward to westward. The area is generally covered with shallow water (0.5 – 1.5 m deep) but high points near the reef crest are exposed at low tide.

ii) Biological Communities

The Rubble and Knob Zone derives its characteristic orange–brown colour from abundant brown algae found attached to the debris (Plate 5.1A). Common are *Padina sp.*, *Dictyota sp.*, *Stypopdium zonale*, *Turbinaria sp.*, and *Sargassum sp.* Red algae is also

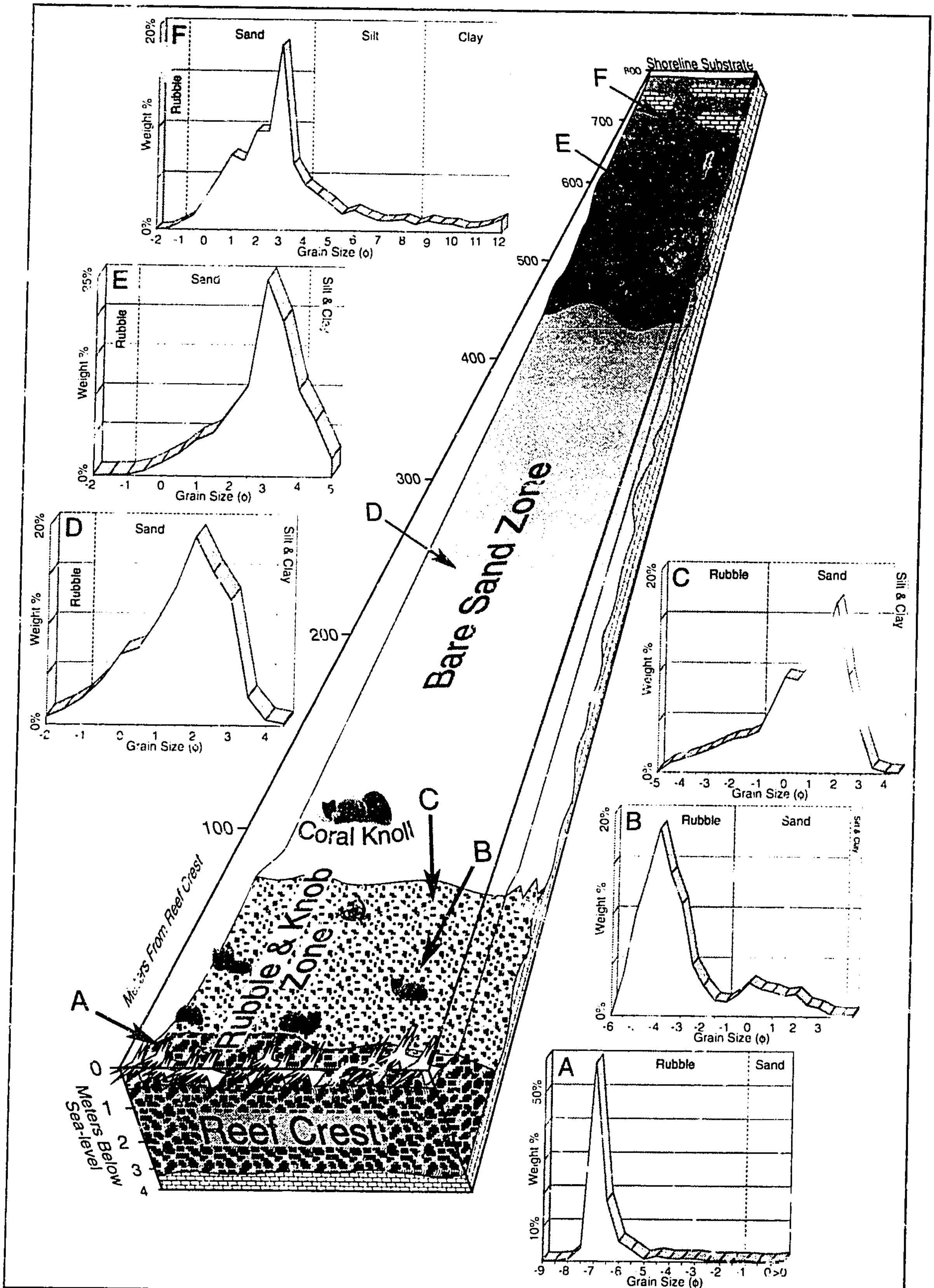


Figure 5.1: Grain-size variation across a representative lagoon transect. A) - C) Rubble & Knob Zone. D) Bare Sand Zone. E) - F) *Thalassia* & Sand Zone.

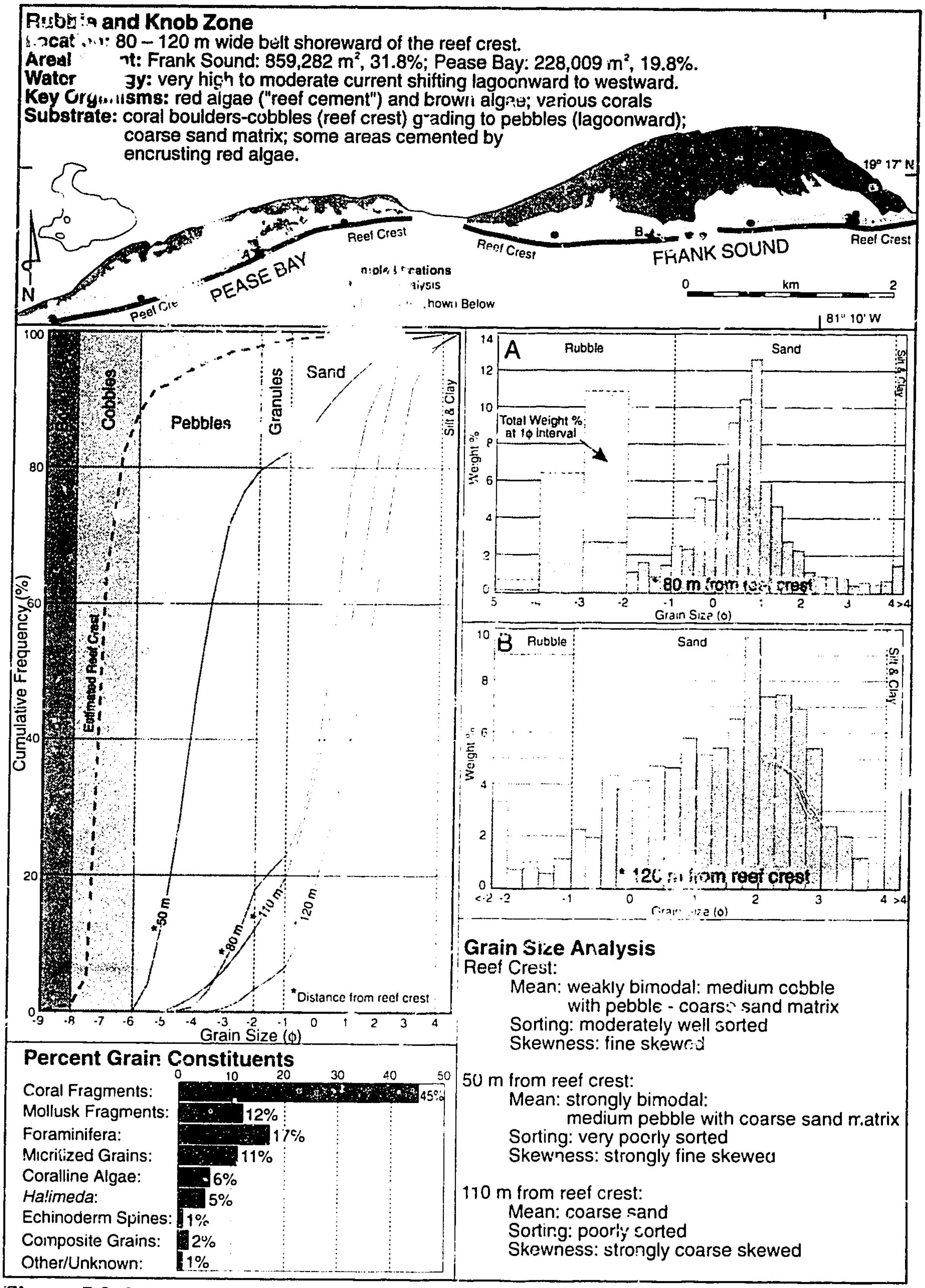


Figure 5.2: Summary of grain size analysis and constituents of Rubble & Knob Zone samples.

Plate 5.1:

A) Brown algae (b) covering rubble of the Rubble and Knob Zone in eastern Frank Sound. Gorgonian in center is ~ 0.5 m tall.

B) Knob of *Porites astreoides*, ~ 30 cm in diameter, in the Rubble and Knob Zone of eastern Frank Sound.

C) Browsing conch (*Strombus gigas*) on bare rippled sand of the Bare Sand Zone, central Pease Bay. Conch is ~ 25 cm long.

D) Green algae *Halimeda* (h), and *Avrainvillea* (Av), with sparse *Thalassia* in the Bare Sand Zone of eastern Frank Sound. *Halimeda* (h) in foreground is ~ 10 cm tall.


B
b
C
h

diverse and numerous; *Acanthophora spicifera*, *Champia sp.*, and other branching varieties are found attached to rubble. The encrusting red algae *Porolithon pachydermum* has completely fused the rubble together in some areas. This is common where the current is strong such as near the reef crest. Green algae, however, are present only in limited varieties and numbers. Some *Halimeda tuna* is associated with the small coral knobs and knolls and *Acetabularia* can be found colonizing the rubble. Other green algae common in the Bare Sand Zone can rarely be found in sandy pockets on the Rubble Flat.

The Rubble and Knob Zone near the reef crest has a high coral diversity with 25 species compared to 20 species found on the neighbouring reef crest (Hunter, 1993). The area near the reef crest is dominated by *Acropora palmata*, which forms robust colonies with thick branches oriented into the wave surge. This is replaced by domal colonies of *Montastrea annularis* and branching *Acropora cervicornis*, and *A. prolifera* a little further back into the lagoon. Other corals here include *Siderastrea siderea*, *S. radians*, *Diploria strigosa*, *D. labyrinthiformis*, *Colpophyllia natas*, *Porites porites*, *P. astreoides*, *Agaricia agaricites*, *Dichocoenia stokesi*, *Favia fragum*, and *Isophyllastrea rigida* (Hunter, 1993; Plate 5.1B). Coral diversity and coral count decreases further away from the reef crest, and domal, boulder, and encrusting varieties dominate. The dominant coral *Montastrea annularis* is found along with *Siderastrea siderea*, *S. radians*, *Diploria strigosa*, *Diploria labyrinthiformis*, *Colpophyllia natas*, *Porites astreoides*, and *P. porites*.

Associated with the corals are a variety of gorgonians, sponges, bryzoans, and hydrocorals. The delicate *Millepora alcicornis* is found lagoonward whereas the more rugged varieties of hydrocoral, *Millepora complanata* and *M. squarrosa*, are found near the reef crest.

The rubble is extensively bored and bioeroded by gastropods, fish, and echinoderms notably *Diadema sp.* and the infamous rock rasping Parrotfish. Nocturnal creatures dwelling under the rubble include fire worms, brittle stars, and octopi. The encrusting foraminifera, *Homotrema rubrum*, which gives near reef sediments a characteristic pink colour, is very common on the undersides of rubble. Other foraminifera are discussed by Li (in prep.).

iii) Sedimentology

Near the reef crest, the Rubble and Knob Zone sediments consists of boulder–cobble sized blocks of broken coral, that grade into cobble–pebble sized rubble further into the lagoon (Fig. 5.1 – 5.3). Size analysis of the rubble from near the reef crest is difficult because of the impracticality of collecting a statistically significant sample and because of large areas covered by encrusting red algae. The proportion of rubble drops rapidly, however, so grain–size analysis is possible half way across the Rubble and Knob Zone.

Grain–size distribution changes rapidly across the Rubble and Knob Zone (Fig. 5.1 – 5.3). The reef crest has a mean grain–size of –7 ϕ (medium cobble) with a matrix of pebbles and coarse sand. Size distribution is bimodal and moderately sorted: the primary mode of medium cobbles greatly outweighs the matrix mode. Moving 50 m behind the reef crest, the primary mode shifts to –4 ϕ (medium pebble). The matrix mode is more pronounced and has a mean of 0 – 1 ϕ (coarse sand). The sediment is very poorly sorted

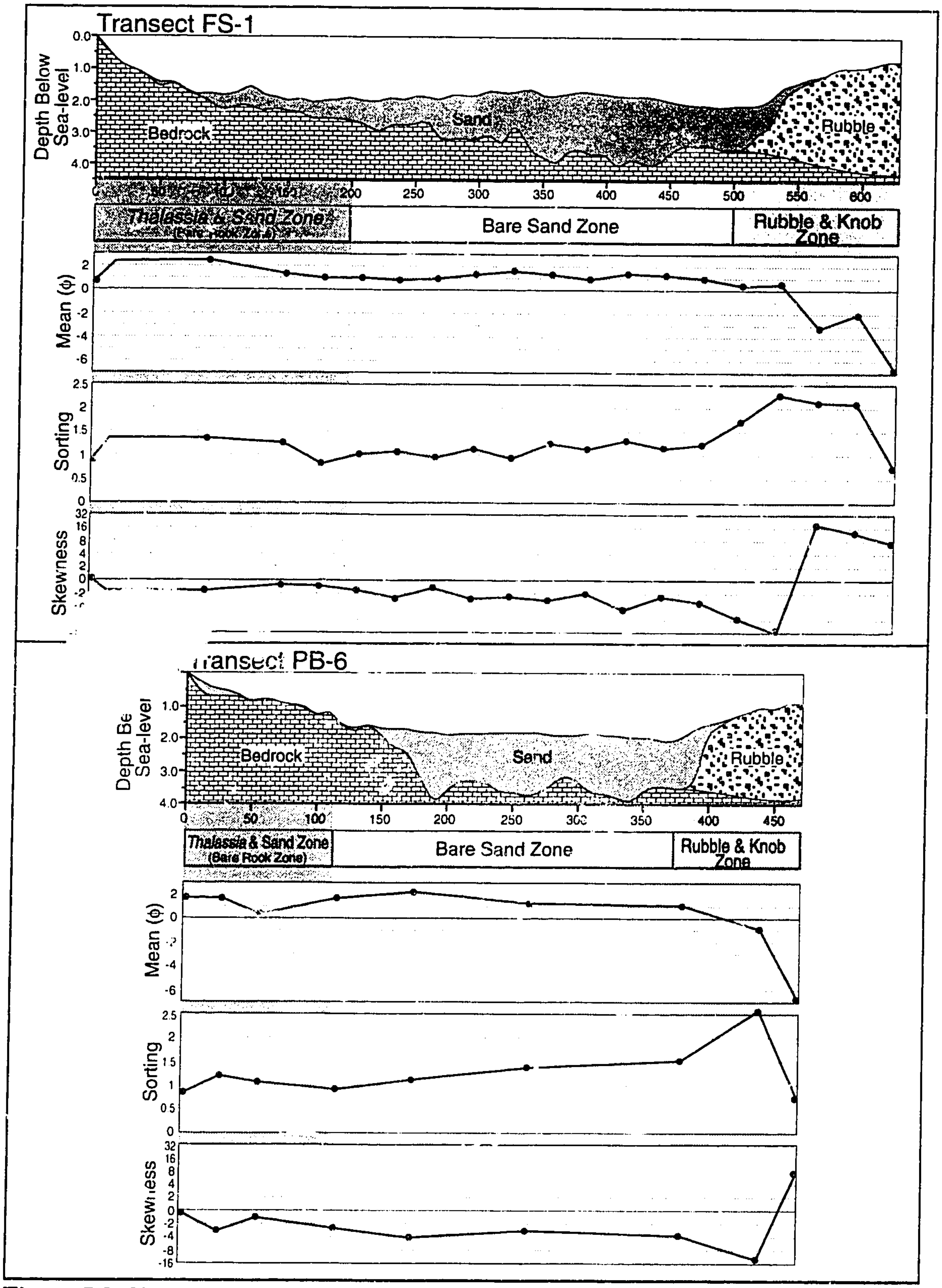


Figure 5.3: Change in grain size distribution across transect FS-1 in eastern Frank Sound and PB-6 in central Pease Bay.

and strongly finely skewed due to the prominent matrix mode. Near the boundary of the Rubble and Knob Zone, 100 m behind the reef crest, the sediment is unimodal or weakly bimodal with a mean size of 0 – 1 ϕ (coarse sand). The sediment is poorly sorted and strongly coarse skewed because of the prominent tail of pebble sized clasts.

The sand of the Rubble and Knob Zone is composed largely of coral fragments (45%), foraminifera (17%), and mollusk fragments (12%) (Fig. 5.2 and 5.4). Fragments of *Homotrema rubrum* constitute over half of the foraminifera. A high degree of micritization rendered many grains unidentifiable (11%). A survey of grain–size fractions in thin section showed composition has no direct bearing on size distribution of the sand fraction.

Areas of rubble in the form of boulder ramparts are found along the headlands of Half Moon Bay, Breakers, and Pease Bay villages. Interestingly, a line connecting these boulder ramparts would trace the reef crest (Fig. 1.1C). These ramparts seem to be an onshore continuation of the rubble deposits that make up the Rubble and Knob Zone. This is supported by the nearly identical size range and composition of rubble from the boulder ramparts and the Rubble and Knob Zone. Rubble from near the reef crest in Frank Sound and Pease Bay has a mean size of medium cobble–small boulder (–7 to –8 ϕ) with a coarse sand and gravel matrix. Rigby and Roberts (1976) described the boulder rampart's mean size as –6 to –9 ϕ with a sorting of 0.5 (well sorted). Composition is also similar. Blanchon *et al.* (in prep.) surveyed 100 cobbles and boulders from four reef crests, including Frank Sound, and found that the rubble was composed of *Acropora palmata* (57%), *Montastrea annularis* (21%), *Diploria sp.* (10%), *Acropora*

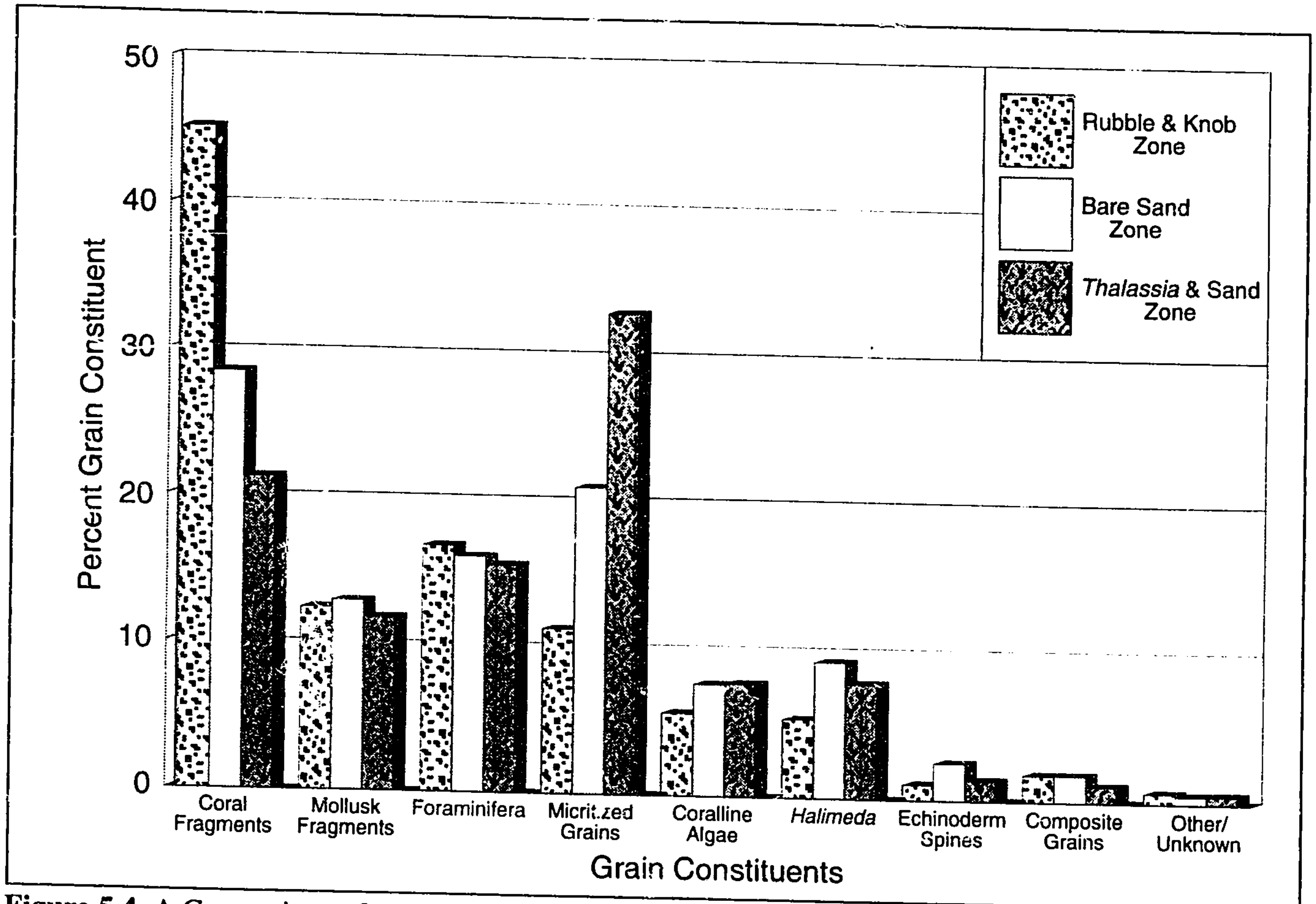


Figure 5.4: A Comparison of grain components of Rubble and Knob Zone, Bare Sand Zone, and *Thalassia* and Sand Zone sediment.

cervicornis (5%), and the remainder was *Siderastrea siderea, Montastrea cavernosa, Colpophyllia sp.*, and *Millepora sp.* Roberts and Moore (1972) surveyed 500 cobbles and boulders from the ramparts on the south side of the island and found *Acropora palmata* (51%), *Diploria strigosa* (14%), *Montastrea annularis* (13%), *Diploria clivosa* (6%), *Montastrea cavernosa* (3%), and the remainder *Diploria labyrinthiformis, Siderastrea siderea, Agaricia spp., Acropora cervicornis*, Ironshore rock fragments, and other corals.

Although the dominant component of the boulder rampart rubble is *Acropora palmata*, Roberts *et al.* (1977) suggested there is no near–shore source. Instead they proposed the rubble originated from the mid–shelf reef and was transported 300 m to shore by hurricanes. Blanchon *et al.* (in prep.) suggested that the Rubble and Knob Zone rubble originated from the *Acropora palmata* growth on the reef crest and directly seaward of this (*see* Stump & Boulder and Spur & Groove Zones of Blanchon and Jones, 1995).

Blanchon *et al.* (in prep.) also examined several channel cuts through the reef crest and found a reef framework with no significant *in situ* coral growth. Instead, the reef is composed of layers of coral boulders and cobbles separated by a thin layers encrusted by red algae. From this they concluded that the reef crest is largely made of hurricane transported rubble generated from the spur and grooves immediately seaward of the reef crest and, to a lesser extent the mid–shelf reef.

2. Bare Sand Zone (BSZ)

i) General

The Bare Sand Zone is a 200 – 300 m wide belt found lagoonward of the Rubble & Knob Zone in water 1.5 – 2.0 m deep (Fig. 5.1 and 5.5). It is characterized by barren sand or sand with sparse sea grass and green algae (Plate 5.1C and D). Currents flow shore–parallel and westward, and are moderate – low in strength. Pease Bay currents are noticeable stronger then those in Frank Sound.

ii) Biological Communities

Green algae are the most prevalent member of the Bare Sand Zone community. *Halimeda incrassata*, *H. monile*, and *Penicillus spp.* are the most common varieties (Appendix C). Less abundant are *Avrainvillea spp.*, *Udotea spp.*, *Caulerpa cupressoides*, and *Acetabularia spp*. The Bare Sand Zone can also have a significant cover of *Thalassia* and manitee grass, *Syringodium filiforme*.

Mounds of sand are found in the Bare Sand Zone near the transition to the *Thalassia* and Sand Zone. They are thought to be made by *Callianassa* shrimp or by the burrowing worm *Arenicola* (Rigby and Roberts, 1976). The intense burrowing activity of these organisms will bioturbate the sediments and also resuspend fine sediments.

Other bioturbating organisms in the Bare Sand Zone include conch (*Strombus gigas*), sea urchins (*Meoma ventricosa* and *Clypeaster subdepressus*), sea cucumbers (*Holothuria mexicans*), feather duster worms (*Bispira variegata*), and fish. Large circular depressions approximately 20 – 40 cm deep and 1 – 1.5 m in diameter were made by burrowing stingrays (*Dasyatis americana*). Coral knolls that are found in the Bare Sand

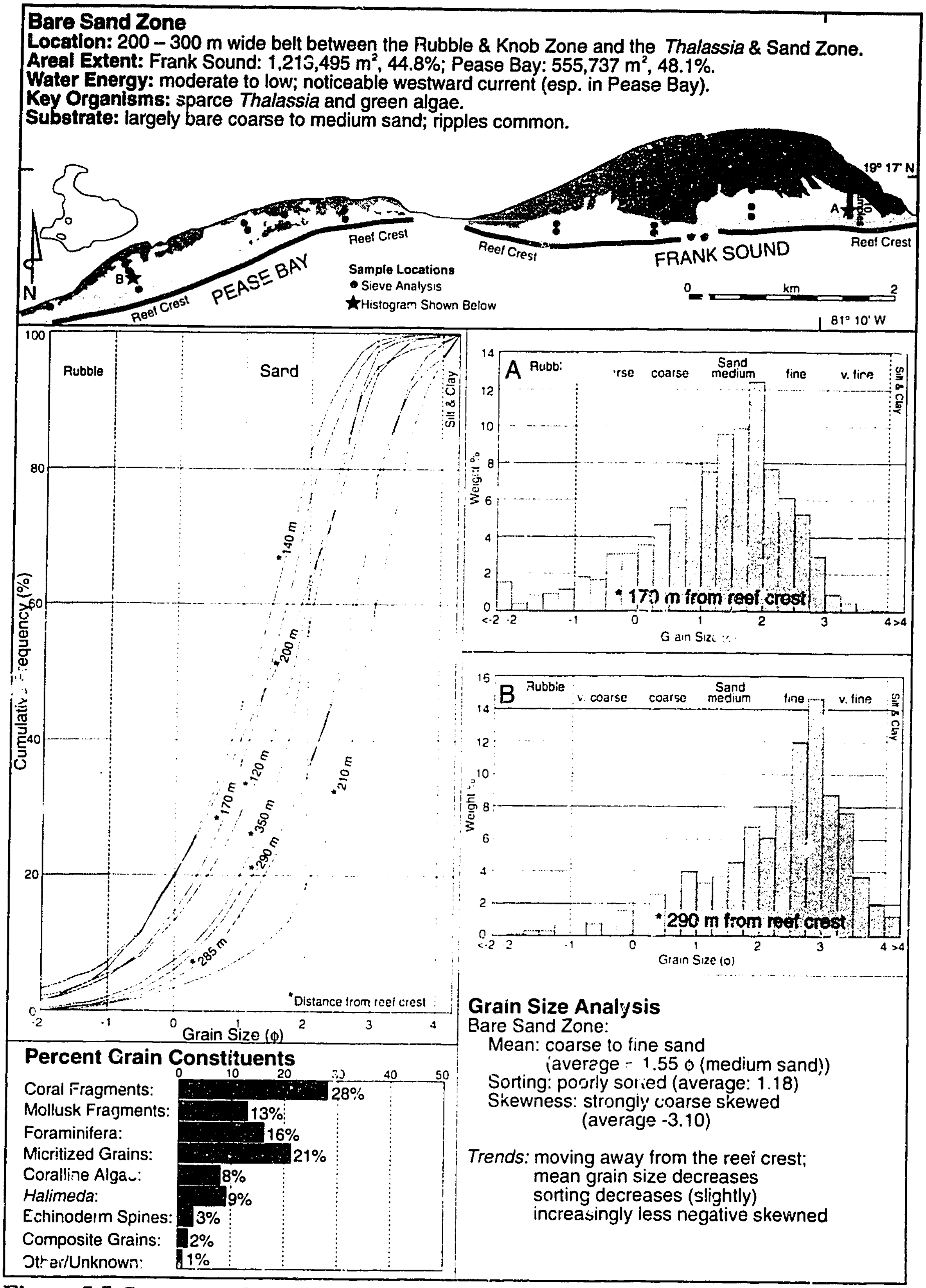


Figure 5.5: Summary of grain size analysis and constituents of Bare Sand Zone samples.

Zone are islands of activity and the home base of many grazing and hunting fish and invertebrates.

iii) Sedimentology

Bare Sand Zone sediment is typically a medium to fine skeletal sand (Fig. 5.1, 5.3, and 5.5). Asymmetrical ripples are common and indicate a shoreward current near the Rubble and Knob Zone and a westward current in the interior. Local variations are related to channels, obstructions to currents, and sediment [illegible] nding plants. Sediments are subject to bioturbation and preservation of primary sedimentary structures is unlikely.

Surface sediments vary across the Bare Sand Zone (Fig. 5.3 and 5.5). Mean grain–size tends to decrease away from the reef crest along each transect, typically changing from medium to fine sand or from coarse to medium sand. Sorting also decreases slightly along individual transects from moderate to poorly sorted. All samples from the Bare Sand Zone are strongly coarse–skewed. Nevertheless, skewness is less negative moving towards shore.

Subsurface sediment shows little variation from surface sediments. Core SCFSf [illegible] grain–size of fine sand, moderate sorting, and strong coarse skewness down [illegible] h of the 134 cm core (Fig. 5.6). Sediment composition is also unchanged. Little or no organic material such as *Thalassia* rhizomes, roots, or staining is found. The entire core consists of clean pink sand, rich with coral fragments, foraminifera (including fragments of *Homotrema rubrum*), mollusk fragments, and *Halimeda*. The only sedimentary structure was a layer of pebbles found 40 cm and 50 – 60 cm below surface in SCFSf and SCFSe, respectively. The pebbles are –3 to –4 ϕ and are composed of coral

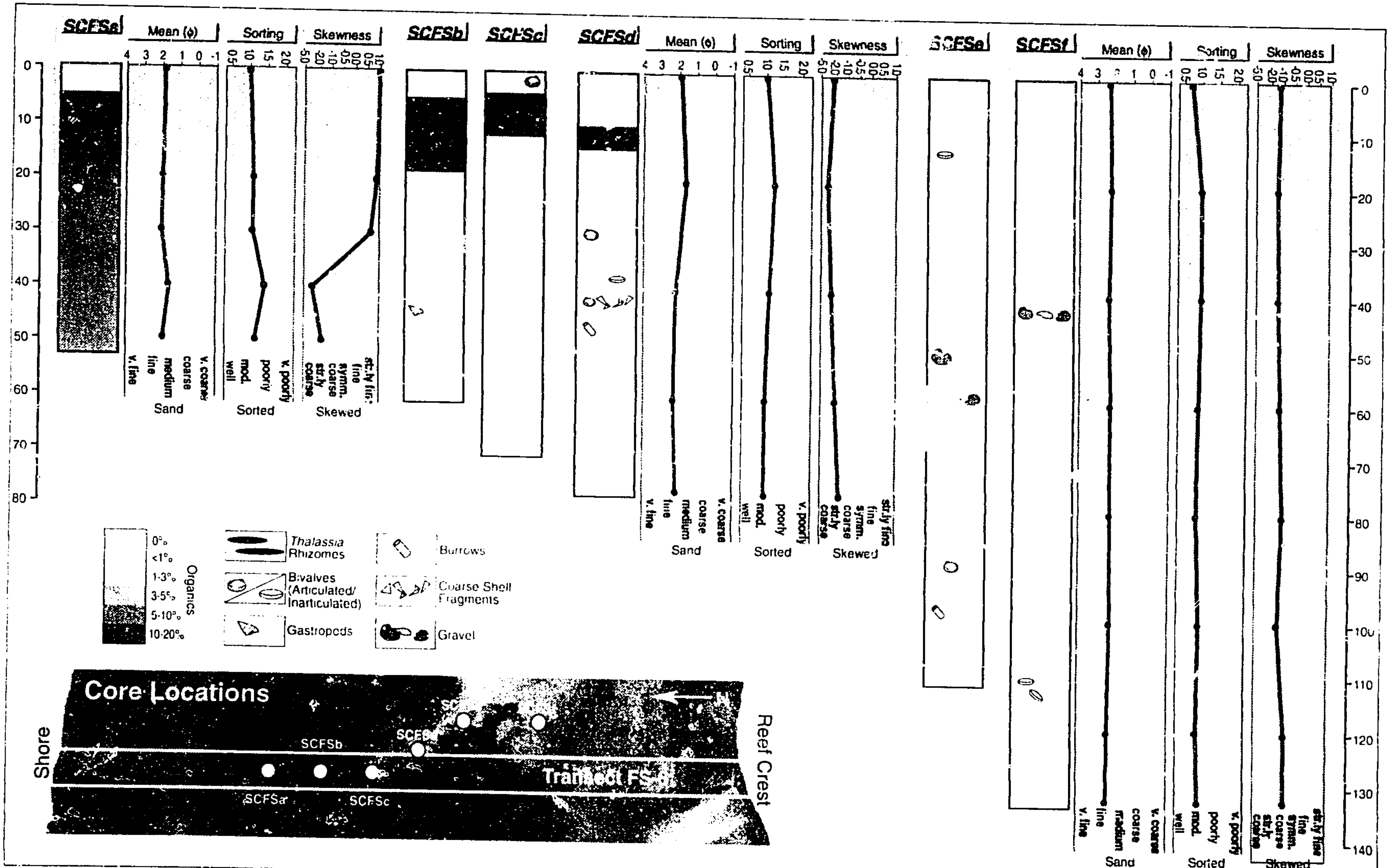


Figure 5.6: Soft sediment cores across the transition from the *Thalassia* & Sand Zone to the Bare Sand Zone on transect FS-6.

encrusted by red algae and *Homotrema rubrum*. A coarse layer of shell fragments was found a 40 cm below the surface in core SCFSd from the transitional zone between the Bare Sand and *Thalassia* and Sand Zones. This layer may be a continuation of the pebble layer found in the other cores.

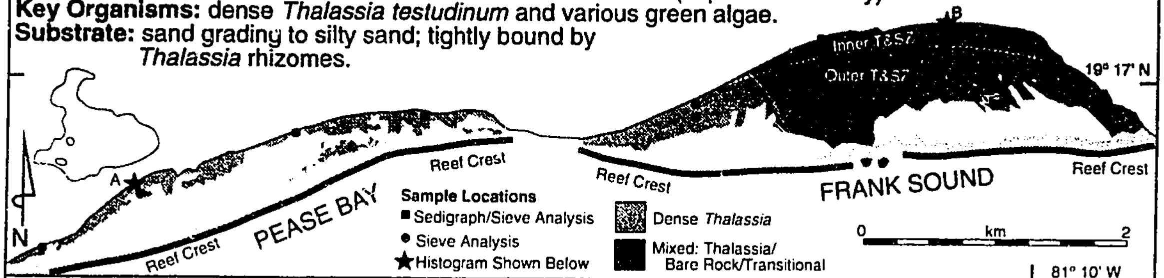
The sediment of the Bare Sand Zone is composed of coral fragments (28%), foraminifera (16%), and mollusk fragments (13%) (Fig. 5.4 and 5.5). The high coral and coralline red algae (8%) content, and the abundance of *Homotrema rubrum* fragments in the foraminifera fraction indicate a extra–lagoonal and/or near reef crest source. The sediment in the Bare Sand Zone contains nearly twice as many micritized grains as the sediment in the Rubble and Knob Zone. A survey of grain–size fractions showed that composition has no direct bearing on size distribution of the sand fraction.

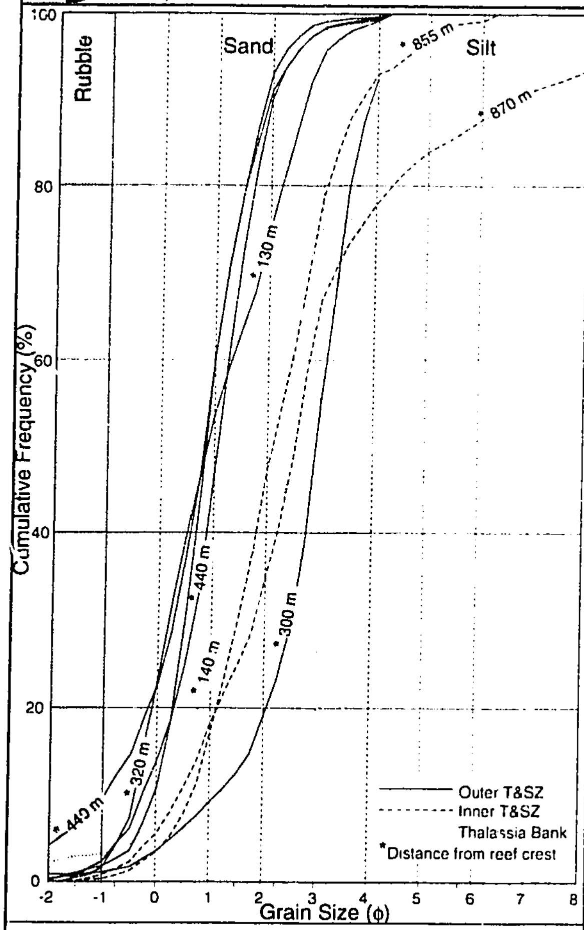
3. *Thalassia* & Sand Zone (TSZ)

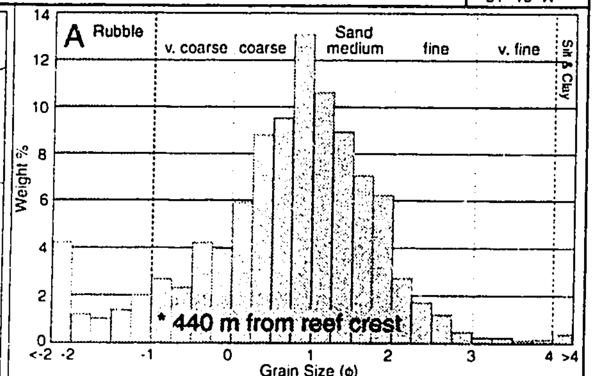
i) General

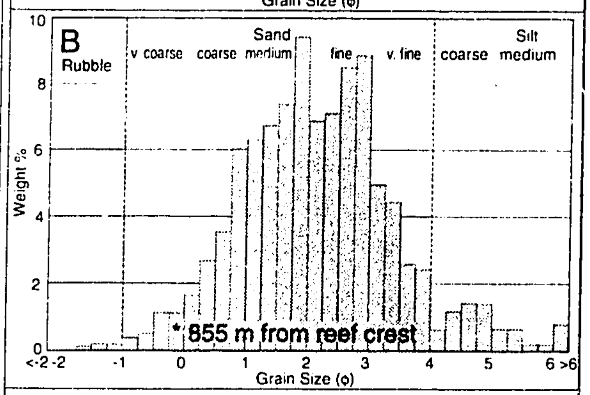
The *Thalassia* and Sand Zone extends from the Bare Sand Zone to near shore and is characterized by a dense growth of *Thalassia* grass in a medium to fine sand (Fig. 5.1 and 5.7; Plate 5.2A). The only area studied where the sediment is > 5% silt and clay is near shore in central Frank Sound, the widest part of the lagoon. This area is termed the Inner *Thalassia* and Sand Zone (Fig. 5.7). Currents are moderate – low in the outer *Thalassia* and Sand Zone, and low in the inner *Thalassia* and Sand Zone. In addition to near shore *Thalassia*, isolated *Thalassia* banks are found adjacent the Rubble and Knob Zone in east Pease Bay. Current is high – moderate over these banks.

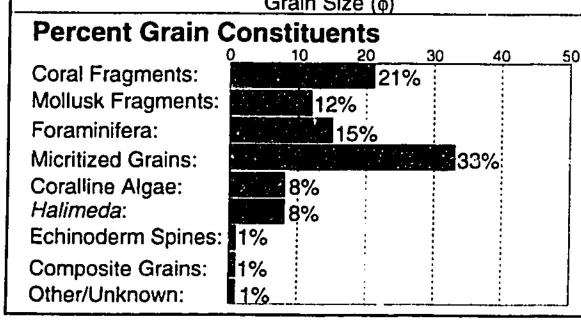
***Thalassia* & Sand Zone** (Bare Rock Zone and Transitional Zone)
Location: extending from Bare Sand Zone to near shore; banks near the reef crest in western Pease Bay.
Areal Extent: Frank Sound: 859,282 m², 31.8%; Pease Bay: 228,009 m², 19.8%.
(Transitional Zone: Frank Sound: 467,718 m² 17.3%; Pease Bay: 142,945 m², 12.4%)
Water Energy: moderate to low; noticeable westward current (esp. in Pease Bay).
Key Organisms: dense *Thalassia testudinum* and various green algae.
Substrate: sand grading to silty sand; tightly bound by *Thalassia* rhizomes.











Grain Size Analysis
Thalassia & Sand Zone:
Mean: coarse to fine sand
(average = 1.90 φ (medium sand))
Sorting: poorly sorted (average: 1.41)
Skewness: strongly coarse changing to strongly fine skewed
(average: outer -3.10; inner +12.46)

Trends: moving away from the reef crest;
mean: grain size decreases
sorting: outer = poorly sorted;
inner = very poorly sorted
skewness: outer = strongly coarse skewed;
inner = strongly fine skewed

Figure 5.7: Summary of grain size analysis and constituents of *Thalassia* & Sand Zone samples..

Plate 5.2:

A) Dense *Thalassia* in eastern Pease Bay's *Thalassia* and Sand Zone. Individual *Thalassia* blades are ~ 30 cm long.

B) Sea urchins (*Tripneustes ventricosus*) with moderate *Thalassia* cover and manatee grass. *Thalassia* and Sand Zone, eastern Pease Bay. Sea urchins are ~ 15 cm in diameter.

C) Conical mounds (~ 30 cm diameter) of *Arenicola* worms or *Callianassa* shrimp partially burying *Thalassia* and manatee sea grass.

D) *Montastrea annularis* coral knoll in eastern Pease Bay. Coral knoll stands ~ 1.5 m tall.

ii) Biological Communities

The *Thalassia* and Sand Zone is dominated by the flat–bladed sea grass *Thalassia testudinum*. Green algae is abundant where grass cover is less dense. The common green algae are *Halimeda incrassata*, *H. monile*, *Penicillus pyriformis*, *P. capitatus*, *Avrainvillea nigricans*, *Udotea flabellum*, *Caulerpa cupressoides*, *Acetabularia spp.* Other flora include brown and red algae, and angiosperms, *Syringodium filiforme* and *Halophilia sp.*

Thalassia testudinum consists of three or four ribbon–like leaves growing from a dense system of horizontally spreading rhizomes. The leaves are 8 – 12 mm wide and 20 – 30 cm long. The density of grass varies and is described as sparse, (< 100 blades/m^2), moderate (~ 100 – 200 blades/m^2), or dense cover (> 200 blades/m^2). The highest count of *Thalassia* was 1,000 blades/m^2 yet typical leaf count was 400 – 500 blades/m^2 (Appendix D). Leaf count and leaf length are comparable to those Raymont *et al.* (1976) found in North Sound in the transitional area between the reef shoal (i.e., Bare Sand Zone) and the richer grass plain.

The inner *Thalassia* and Sand Zone of Frank Sound had only 2 – 3 cm of leaf detritus, the maximum for the study area, compared to 30 cm found in the calmest areas of North Sound (Raymont *et al.*, 1976). Broken *Thalassia* blades were observed floating westward in Pease Bay at approximately 16 cm/sec after a brief summer squall. *Thalassia* leaves were continuously washed onshore in the study area. The thickest shore accumulation was 40 cm thick and 1 m wide along the beach near Betty Bay Pond (west Frank Sound).

The sea grass community has a much higher species diversity than the neighbouring Bare Sand Zone, though few species feed directly on *Thalassia* leaves. Most important among these are the short spined sea urchins. The 'decorator sea urchin', *Tripneustes ventricosus*, is common whereas *Meoma ventricosa* is less numerous (Plate 5.2B). Vertebrates such as the green turtle (*Chelonia mydas*) and Parrotfish (*Sparisoma radians*) also graze on sea grass.

Thalassia does not secrete any carbonate inside its leaves or roots. It does, however, support a variety of carbonate epibionts on the leaves including foraminifera, serpulid worms, and coralline algae. Leaf growth is from the base of the plant upward, so the longest, oldest blades tend to be chalky and covered with covered with epibionts. Upon death and disintegration of the blades the epibionts breakdown into mud and some silt–sized crystals.

Mollusks are well represented in the *Thalassia* and Sand Zone. Common and conspicuous gastropods are conch (*Strombus gigas* and *S. costatus*), *Cerithium litteratum*, and *Fasciolaria tulipa*. Noticeable bivalves include *Tellina radiata* and *Pinna carnea*.

Free–living colonies of *Porites divaricata*, *Siderastrea radians*, and *Favia fragum* are found in the *Thalassia* and Sand Zone and landward Bare Rock substrates (Hunter, 1993). These species are tolerant of short term fluctuations in temperature and salinity, and siltation that can occur in the back lagoon.

The conical mounds recognized in the Bare Sand Zone are more common in the *Thalassia* and Sand Zone (Plate 5.2C). The mounds are typically 30 cm in diameter with a 'crater' on the top. Two organisms construct such mounds, *Arenicola* or 'Lugworms' and *Callianassa* shrimp. In areas where mounds are especially common the neighbouring *Thalassia* is blanketed by a fine sediment that is exhaled from the top of the mounds.

As in the Bare Sand Zone, coral knolls are a center of activity in the *Thalassia* and Sand Zone. They serve as day time residence for nocturnal creatures such as octopi, sea urchins (*Diadema*), and fish. Coral knolls that are found in the *Thalassia* and Sand Zone are often ringed by bare sand due to overgrazing by knoll–based herbivores.

iii) Sedimentology

Surface sediment of the *Thalassia* and Sand Zone is typically a medium to fine skeletal sand (Fig. 5.1, 5.3, and 5.7). Mean grain–size tends to decreases whereas sorting changes from poorly to very poorly sorted towards shore along individual transects. Skewness is negative in the outer *Thalassia* and Sand Zone areas of Frank Sound and all of Pease Bay. The inner *Thalassia* and Sand Zone in Frank Sound experiences an abrupt shift from negative to strongly fine skewed as silt content increases.

The inner *Thalassia* and Sand Zone of Frank Sound is the only area with significant silt and clay, the maximum recorded was 15% dry weight. Sediment with a silt and clay fraction > 10% is rare even in this calm near–shore area. The fine fraction is dominantly coarse and medium silt and weight percent drops abruptly near the medium – fine silt boundary (Fig. 5.7; histogram B). Clay sized sediment is very rare.

Subsurface sediment shows little variation in grain–size and sorting from surface sediments (Fig. 5.6). Core SCFSa has a mean grain–size of fine – medium sand and poor sorting over the entire length. Skewness, however, makes a dramatic shift from strongly fine skewed in the *Thalassia* rhizome and root rich upper layer, to strongly coarse skewed below. Like cores from the Bare Sand Zone, the sediment is formed of grains derived from corals, foraminifera (including fragments of *Homotrema rubrum*), mollusks, and *Halimeda* over the entire length of core. Organic content is high due to a dense layer of *Thalassia* rhizomes (5 – 18 cm), and *Thalassia* roots down to the bottom of the core (Fig. 5.6). Cores from the transition between the *Thalassia* and Sand Zone and the Bare Sand Zone have a progressively smaller and less–rich organic layer.

Sediment in the *Thalassia* and Sand Zone is composed of coral fragments (21%), foraminifera (15%), and mollusk fragments (12%) (Fig. 5.4 and 5.7). Sediment constituent analysis was complicated by intense micritization. One sample from the inner *Thalassia* and Sand Zone had ~ 70% unidentifiable grains due to micritization. As in the Rubble and Knob Zone and Bare Sand Zone, composition has no direct bearing on size distribution of the sand fraction.

Oncoids are common on current swept *Thalassia* banks on the lagoon flanks and near the reef crest in Pease Bay. They are typically 2 – 3 cm long, 1.5 – 2.2 cm wide, and 1.6 cm high (Jones and Goodbody, 1985). Sample processing and sieve analysis broke down the oncoids and resulted in a unusual bimodal size distribution. The primary mode is medium sand and the secondary mode, believed to result from the breakdown of oncoids, is very fine sand.

Thalassia beds are highly energy resistant because of their extensive system of rhizomes that stabilize and bind the sediment. Dense communities can withstand currents up to 150 cm/sec (Neumann *et al.*, 1970). Rhizomes are 10 – 20 cm below the surface and roots are found at least 40 cm deeper (Fig. 5.6). Despite this some erosional features are found. "Blowouts" are crescent shaped erosional depressions formed in areas of moderate to high wave energy (Neumann *et al.*, 1970). The seaward convex edge is steep or undercut, exposing the rhizomes, and the depression can contain a lag deposit. Blowouts are thought to be initiated by storm waves and later enlarged and migrate through normal wave energy. The defoliated area is later reclaimed and stabilized by green algae, manitee grass, and eventually *Thalassia*.

The sediment binding (Neumann *et al.*, 1970), current baffling (Almasi *et al.*, 1987), and epibiont sediment production (Stockman *et al.*, 1967; Nelsen and Ginsburg, 1986) of *Thalassia* can result in elevated plateaus or sea grass banks. Excellent examples of banks are found in eastern Pease Bay at the edge of the Rubble and Knob Zone. They rise nearly 1 m above the surrounding lagoon floor (Fig. 3.7; transect PB–2 and PB–8). Less pronounced banks are also found throughout the *Thalassia* and Sand Zone in Pease Bay and eastern and western Frank Sound. Central Frank Sound is characterized by a subdued *Thalassia* plain rather than prominent banks.

C. MINOR LAGOON SUBSTRATES

1. Bare Rock Zone (BRZ)

The Bare Rock Zone consist of stripped bedrock with pockets of loose sand. Areas of bare rock are limited in extent, so the sparse sediment is similar in composition and grain–size to that of the neighbouring major substrates. Exposures of bare rock are found 1) near shore in a shore–parrallel strip, 2) on the lagoon flanks, and 3) adjacent to Frank Sound channel. Each of these areas experience high energy conditions during storms.

Lagoon transects show near–shore bare rock areas are found where bedrock is 1.5 – 2.0 m below sea–level (Fig. 3.5 – 3.7). In the few areas where near–shore bedrock is > 2 m below sea–level and sediment is thick, well rooted *Thalassia* beds grow up to the shore or end abruptly at the edge of the beach in a undercut scarp similar to a blowout (Fig. 3.5; transect FS–4 and FS–2). No bedrock is exposed.

The situation is similar on the lagoon flanks and near the Frank Sound channel opening. The area from the channel to 300 m north is almost completely stripped of sediment and sediment thickness rarely exceeds 0.5 m across the entire lagoon adjacent the channel (Fig. 3.5; transect FS–7). It is interesting to note the relation between *Thalassia* and bare rock substrates with bedrock topography in this area. Bedrock 'potholes' filled with sediment are colonized by *Thalassia*. Conversely, areas of higher bedrock topography lack *Thalassia* and significant sediment. This patchwork of substrates covers a roughly triangular region emanating from the channel opening (Fig. 5.7).

Biologic communities in the Bare Rock Zone are similar to the neighbouring major substrates. Near–shore bare rock usually has pockets or a thin veneer of sediment (1 – 3 cm) that allows for limited *Thalassia* and green algae communities. The *Thalassia*, however, will be sparse and poorly rooted. Small colonies of *Porites divaricata*, *Siderastrea radians*, and *Favia fragum* are found where sediment is thin or absent (Hunter, 1993). The lagoon flanks and near the Frank Sound channel have a more diverse coral assemblage (similar to the Rubble and Knob Zone), coral knoll communities, gorgonians, sponges, coralline red algae, and abundant brown algae.

2. Coral Knolls

Coral Knolls are localized coral–based communities found in the Bare Rock Zone, Rubble and Knob Zone, Bare Sand Zone, and rarely on the *Thalassia* and Sand Zone. They require a hard substrate and therefore are most common on bedrock outcrops or stable rubble. The largest examples and greatest numbers of coral knolls in the study area are found near the Frank Sound channel, where knolls are up to 3 m high and 30 m in diameter. More typical, however, are small knolls 1 – 2 m high and < 5 m in diameter (Plate 5.2D). These consist of 1 – 3 large coral heads, commonly of the same species, and a few associated corals.

Most of the coral knolls are dominated by large colonies of *Montastrea annularis* and *Siderastrea siderea*. Other relatively common corals are *Montastrea cavernosa*, *Diploria strigosa*, *Porites porites*, *P. astreoides*, and *Agaricia agaricites*. Lesser numbers of *Diploria labyrinthiformis*, *D. clivosa*, *Acropora cervicornis*, *A. palmata*, *Agaricia fragilis*, *Madracis mirabilis*, and *Siderastrea radians* are also found. Coral diversity decreases as distance from the reef crest increases. Coral knolls found at the Frank Sound channel opening have the highest diversity whereas knolls found 500 m further north consisted of only *Montastrea annularis*, *Porites porites*, and *P. astreoides*.

Living on the framework provided by the corals is a diverse community of gorgonians, sponge, hydrocorals (e.g., *Millepora complanata*, *M. alcicornis*), green algae (e.g., *Halimeda tuna*, *Acetabularia spp.*, 'sea pearls'), brown algae (e.g., *Padina sp.*, *Dictyota sp.*, *Stypopodium zonale*), coralline red algae (e.g., *Galaxaura sp.*, *Amphiroa sp.*), and a variety of mollusks. The knolls are also the center of activity and shelter for numerous fish species, lobster, octopi, anemones, and sea urchins (e.g., *Diadema*).

Coral knolls are a local source of carbonate sediment. Areas adjacent and down current from knolls had a noticeable increase in large coral fragments, such as pebble size pieces of *Porites*, and appeared richer in *Halimeda* sand. Coral knoll sediment, however, will likely be transported since it is found in areas where storm energy is concentrated.

3. Shoreline Substrates

Most of the shoreline of Frank Sound and Pease Bay consists of a moderately narrow, steep faced beach extending < 5 m on and off shore from mean sea–level. Small exposures of bedrock are found along most of the shoreline and cover larger stretches of the shore in eastern Pease Bay, Pease Bay Point, and western Frank Sound.

The limited wave energy passing over the reef crest breaks on the shore substrates resulting in moderately high water energy. Evidence of a weak westward longshore current is seen where bedrock outcrops form natural jetties and collect sediment on the up–current sides.

Beach sands are typically medium to coarse sand with an average mean grain–size of 1.4 ϕ (medium sand), moderate sorting (0.75 average), and coarse skewness (–0.32 average). Cobble–sized coral rubble is a common constituent of beach deposits in areas where the reef crest is near shore. Beachrock was found at only one location in eastern Pease Bay. The foraminifera assemblage of beach sand indicates a near–shore lagoonal source for beach sediment (Li, pers. comm.). It is probably transported from near–shore areas during storms, producing the shore–parallel Bare Rock Zone.

Shoreline substrates have communities of terrestrial, intertidal, and marine organisms. The beach is dominated by land and marine crabs that are responsible for extensive burrowing. The undercut scarp of near–shore *Thalassia* beds is inhabited by crabs and lobster, and schools of young fish are common. The rocky shoreline areas are extensively bored and encrusted.

D. SYNOPSIS: SEDIMENTOLOGY AND BIOLOGICAL COMMUNITIES

A typical lagoon transect from reef to shore crosses three main substrates, the Rubble and Knob Zone, the Bare Sand Zone, and the *Thalassia* and Sand Zone. Three additional minor environments are also recognized, the Bare Rock Zone, coral knolls, and shoreline substrates (Fig. 5.1). The area north of the Frank Sound channel is the only major divergence from the typical reef to shore substrate succession. There, a patchwork of *Thalassia* grass and bare rock covers a roughly triangular region emanating from the channel opening (Fig. 5.7). Sediment is thin or absent throughout this area.

Sediment grades from cobble sized rubble near the reef crest to coarse sand at the lagoonward edge of the Rubble and Knob Zone. Grading continues across the Bare Sand Zone and *Thalassia* and Sand Zone, from coarse to medium–fine sand. Silt and clay sized sediment are rare in Frank Sound and Pease Bay: the only significant amount is found near shore in central Frank Sound.

In general, sorting increases slightly across the Rubble and Knob Zone, Bare Sand Zone, and most of the *Thalassia* and Sand Zone (Fig. 5.3). Except for the reef crest area where sorting is moderate, the Rubble and Knob Zone sediment is very poorly sorted. The Bare Sand Zone is typically poorly to moderately sorted and most of the *Thalassia* and Sand Zone is poorly sorted. The inner *Thalassia* and Sand Zone sediment is very poorly sorted because of the increased silt content (Fig. 5.7).

Grain–size distribution of lagoonal sediments is predominately Gaussian in nature. No distinctly polymodal sediment was found in the lagoons except in the Rubble and Knob Zone near the reef crest (Fig. 5.1, 5.2, 5.5, and 5.7). There, the primary mode consists of coral rubble and the secondary mode is matrix sand. A survey of grain–size fractions in thin sections from each of the major zones, shows composition has no direct bearing on size distribution of the sand fraction.

The major constituents of lagoonal sediment are coral fragments, foraminifera, and mollusk fragments. Coral, coralline red algae, and the foraminfera *Homotrema rubrum* are found in all parts of the lagoon indicating an extra–lagoonal sediment source and shoreward sediment movement.

Subsurface sediment is similar in grain–size and composition to surface sediments from the top of the cores. A layer of coral pebbles is found 40 – 60 cm below the surface in the two cores from the Bare Sand Zone.

VI. DISCUSSION AND CONCLUSIONS

A. FAIR–WEATHER AND STORM PROCESSES

The relative importance of environmental processes that affect sediment distribution vary with the intensity and frequency of the processes. Although fair–weather processes have some influence on the sediment of Frank Sound and Pease Bay, storm processes are much more intense and greatly overprint any fair–weather effects. Hurricanes are by far the most important agents in controlling the distribution of lagoonal sediment and biota.

Under fair–weather conditions local sediment production, bioerosion, bioturbation, and *Thalassia* colonization dominate. In general sediment production is low and restricted to *Thalassia* epibionts, limited coral growth, and some algae, foraminifera, and mollusks. *Thalassia* advances relatively quickly over the Bare Sand Zone and fills in areas of sparse cover in the *Thalassia* and Sand Zone.

Under fair–weather conditions there is a influx of wave driven water over the reef crest (Suhayda and Roberts, 1977). Water exits Frank Sound through the central channel and, to a lesser extent, out the west end of the lagoon. Pease Bay lacks a major channel, so the excess water is funneled out the west end of the lagoon. Rip currents are found at each of these locations.

Fair–weather wave action over the reef crest and lagoonal currents move only minor amounts of sediment. Some shifting of sediment takes place in the Rubble and Knob Zone and near channels, and fine material from the Bare Sand and *Thalassia* and Sand Zones is suspended by infaunal activity and transported out of the lagoons by fair–

weather currents. An illustration of the removal of fines is seen in the 1992 aerial photographs as a faint sediment plume visible seaward of the Frank Sound channel.

In general, fair–weather waves and currents have only minor effects on the distribution of sediment and biota, and *in situ* lagoonal production is low. Historical records, however, show Grand Cayman is affected by severe storms and hurricanes on a regular basis. Hurricanes pass directly over the island on average once every ten years (Clark, 1988), although their recurrence interval and intensities vary. Records describe especially severe hurricanes in 1785, 1836, 1876, 1910, and 1932 (Hirst, 1910; Williams, 1970). Hurricanes approaching from the south or south–east would have the greatest effect on Frank Sound and Pease Bay. Eyewitness accounts describe a hurricane in 1910 that approached from east–southeast and caused extensive damage to the south and east ends of the island. One account reported that... "the sea rose up to 15' (4.5 m) and washed away roads and deposited cobble and boulder ridges on shore". Such accounts suggest that hurricanes are both agents of deposition and erosion, and must have a significant impact on all shelf substrates including lagoons.

Frank Sound and Pease Bay substrates can be broken into two domains based on the effects of hurricane processes; 1) *areas of sediment deposition*, characterized by the succession of the three reef parallel zones; the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones, and 2) *areas of sediment removal*, characterized by the Bare Rock Zone. Areas of sediment deposition are related to turbulent, sediment laden currents that sweep over the reef crest during hurricanes and deposit sediment in the lagoons. Conversely, areas of sediment removal are related to the intense currents that drain the lagoons of storm piled water. The nature of these waves and currents is difficult to ascertain from only their effects on the sediment and biota.

The study of hurricane processes in coastal environments has been greatly limited by their violent nature. Consequently, studies have focused on the effects of hurricanes rather than the processes (Flood and Jell, 1977; McKee, 1959; Mah and Stern, 1985; Harmelin–Vivien and Laboute, 1986; Blair *et al.*, 1994). Hubbard's (1992) study of hurricane Hugo's impact on St. Croix is a noteworthy exception. He found, as the hurricane approached, the dominant process was wave piling on the windward shore. As the storm passed, wind direction changed and wave height dropped triggering intense offshore currents draining the trapped water. Similar processes probably occurred in Frank Sound and Pease Bay.

Hurricane processes can be divided into two stages: the hurricane approach and the waning stage as the storm passes. At the peak of the storm, wave height and wave overtopping of the reef crest will be at a maximum (Fig. 6.1A and C). As they pass over the open shelf, hurricane waves and wind–driven currents will entrain a complete range of sediment sizes from various shelf and coastal sources (Hernandez–Avila *et al.*, 1977; Jones and Hunter, 1992; Blanchon and Jones, 1995). Upon reaching the mid–shelf escarpment the waves encounter an abrupt change in depth that initiates spilling and breaking of waves transforming wave energy into a turbulent shoreward current (Fig. 6.1C). This sediment laden current sweeps over the reef crest and, on encountering the shallow lagoon floor, looses energy due to frictional attenuation. As energy is lost, the water looses its capacity to transport sediment, and deposits a sediment wedge that

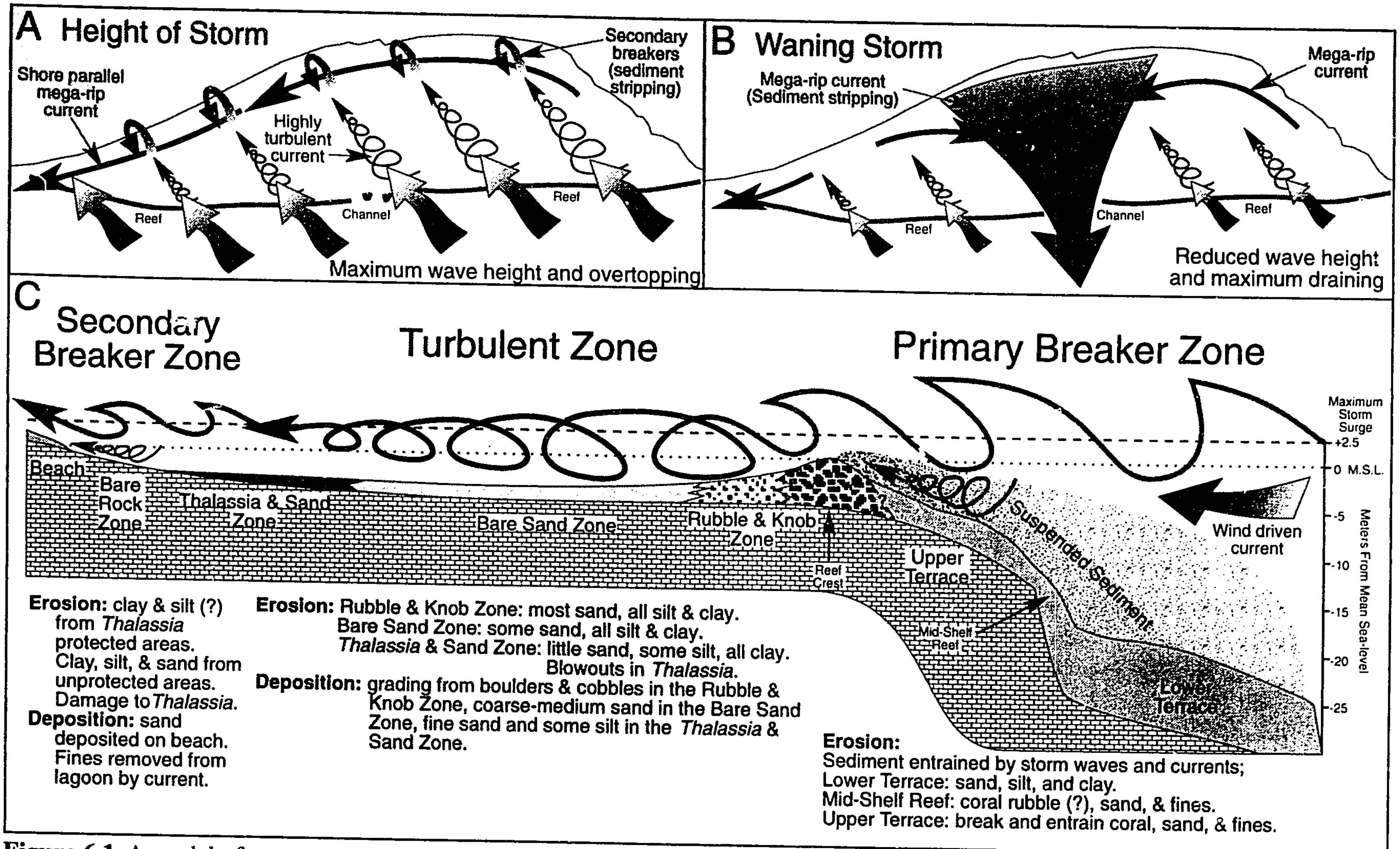


Figure 6.1: A model of storm waves and currents in Frank Sound and Pease Bay. Map view of Frank Sound at, A) the height of the storm, and B) as the storm wanes. C) A profile acoss the lagoon and adjacent shelf during a severe storm.

grades from the coarsest material near the reef crest to finer sediment near shore. This accounts for the decreasing grain–size across the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones, respectively. This turbulent current also suspends fine sediment accumulated during fair–weather. This sediment is transport shoreward or removed from the lagoons by storm currents.

Wave energy that is not broken over the upper terrace and reef crest area will break on shore as secondary breakers (Fig. 6.1A). This accounts for near–shore areas of stripped bedrock found in areas where bedrock is 1.5 – 2.0 m below sea–level (Fig. 3.5 – 3.7). This is probably the level to which near–shore lagoon storm energy — secondary storm breakers and intensified lagoon currents — are able to strip away sediment and rip up *Thalassia*. The sediment is probably transported to the beach or removed from the lagoons by storm currents.

During peak storm conditions, water passing over the reef is many orders of magnitude greater than fair–weather influx. At this stage, the establishment of a return current over the reef is inhibited by a strong onshore wind–driven current and high waves. Some of the water will probably drain from the lagoon in a west–flowing mega–rip current that passes out the western flank of the lagoon. Much of the water will, however, remain piled in the lagoons until later in the storm.

The dominant process during the waning phase of the storm is the draining of storm piled water. As the storm passes over the island, the wind shifts, and wave height and overtopping of the reef crest decrease. This allows water to follow similar routes as currents produced during fair–weather, in topographically controlled mega–rip currents

(Fig. 6.1B). The lagoon floor north of the Frank Sound channel serves as a testimony to the extraordinary power of mega–rip currents. Up to 300 m north of the channel nearly all sediment has been stripped, and sediment thickness rarely exceeds 0.5 m in a roughly triangular region emanating from the channel all the way to shore, just over 1000 m (Fig. 5.7). The west end of Pease Bay will experienced similar high energy storm currents.

B. DISCUSSION

In addition to the evidence provided by decreasing grain–size trend across the lagoon, several other aspects of sediment analysis support the interpretation of storm energy dominated sedimentological processes. First, the size distributions of nearly all of lagoonal sediment has a unimodal distribution. If the lagoonal sediment was a primarily *in situ* biogenic deposit, sediment would be polymodal with modes corresponding to the primary breakdown sizes of the constituents. Sediment size distributions in Frank Sound and Pease Bay, however, are unimodal — a distribution that typically indicates physically dominated systems — and mean grain–size is not determined by peaks in constituent content. Second, sorting is consistently poor across lagoon transects. This again indicates a single dominant process affecting the entire width of the lagoon and suggests sediment was deposited rapidly and en masse during a storm event.

The composition of lagoon sediment also presents a strong case for a physically dominated shoreward transport system. Even in the most distal areas of the *Thalassia* and Sand Zone, sediment is made up of a disproportionately high amount of coral and coralline red algae (Fig. 5.3). Also, fragments of *Homotrema rubrum*, an encrusting foraminifera typically found living on rubble near the reef crest, are found in all lagoonal sediments. This suggests the source of the sediment is the reef crest or fore–reef. Support for this interpretation can be found in the distribution of foraminifera (Li, in prep.). Foraminifera species diagnostic of the fore–reef environment are found in all parts of the lagoon including the *Thalassia* and Sand Zone, again suggesting an extra–lagoonal source for sand sized sediment. Coarse sediment, such as that found in the Rubble and Knob Zone, is more likely to originate from coral growth on the reef crest and directly seaward of this because it is dominated by the shallow water coral *Acropora palmata* (Blanchon *et al.*, in prep.).

Collectively, the evidence from size distribution, sorting, and composition clearly points to the storm entrainment of sediment from the fore–reef areas and deposition, en masse, in the lagoons.

The distribution of lagoon biota — especially *Thalassia* grass — is also significantly influenced by storm processes. Most fair–weather wave energy is broken and absorbed at the reef crest and Rubble and Knob Zone, leaving the rest of the lagoon quiescent (~ 80% of lagoon area) and suitable for colonization by *Thalassia*. Image analysis of changes in the distribution of *Thalassia* over time in Pease Bay show that, at the current rate of expansion, *Thalassia* should completely overgrow the Bare Sand Zone in ~ 70 years. *Thalassia* colonization therefore, must be limited by a natural force that counters this rapid expansion. Uprooting was observed in Bodden Bay (the westward extension of Pease Bay) after prolonged southeasterly winds in March, 1975 (Raymont *et al.*, 1976). Whole *Thalassia* turfs were ripped–up and washed on shore. This was attributed to high waves passing over the reef crest and a strong current draining the excess water from the lagoon. This minor storm event probably ripped up only previously damaged *Thalassia* turfs, such as the undercut blowout scarps, but it is an example of the destructiveness of storms. During more severe storms and hurricanes the impact of currents and waves will be much more harsh. This is demonstrated by blowouts found over 500 m from the reef crest in Frank Sound. It is also the likely origin of 'storm scars' — linear bodies of bare sand oriented south south–east extending into the *Thalassia* and Sand Zone (Fig. 4.7; eastern Frank Sound).

The current speed required to remove the sand from the rhizomes of sparse, medium, and dense *Thalassia* communities is 50, 100, and 150 cm/sec, respectively (Scoffin, 1970; Neumann *et al.*, 1970). Therefore, near–shore current in Frank Sound must have been in excess of 50 cm/sec in order to defoliate the sparse *Thalassia* as well as the shore parallel Bare Rock Zone, now being recolonized. Further from shore, where sediment is thicker and *Thalassia* growth is more dense, currents must have exceeded 100 cm/sec.

The stability of *Thalassia* during storms is related to sediment thickness. Raymont *et al.* (1976) found the health of *Thalassia* communities in North Sound, as indicated by leaf density, was directly related to sediment thickness. In areas of thin sediment (0 – 5 cm) *Thalassia* was poorly rooted and had low leaf counts. Scoffin (1970) found the current speed required to up root *Thalassia* was related to leaf density. In Frank Sound and Pease Bay, much of the *Thalassia* growth found near shore is colonizing areas of thin sediment. Consequently, it is sparse – moderate in density and has low leaf counts. This near–shore *Thalassia* is susceptible to storm damage and will probably be periodically defoliated by storm currents and waves. A further example of the relationship between storms and *Thalassia* is found at the boundary between the *Thalassia* and Sand and the Bare Sand Zones. Here, the sediment is thicker and could potentially support a more lush and storm resistant growth. This area is, however, subjected to even greater storm currents and waves because it is closer to the reef crest (~ 300 m). The *Thalassia* front that advances during fair–weather is periodically ripped up during storms. One final illustration of the relationship of sediment thickness, *Thalassia* stability, and storm defoliation is found in central Frank Sound, the area subjected to the mega–rip current draining the lagoon of storm water. From shore to 300 m from the channel, areas of high bedrock have little sediment and *Thalassia* is absent or very sparse. Whereas, bedrock 'potholes' filled with sediment support moderate – dense *Thalassia*. This implies storm currents were able to rip up poorly rooted *Thalassia* but not the *Thalassia* rooted in deeper sediment (currents > 50 cm/sec but < 100 cm/sec). The area north of the channel storm currents likely exceed 100 cm/sec since *Thalassia* is largely absent and bedrock is stripped. During fair–weather, *Thalassia* in Frank Sound and Pease Bay will then recolonize areas of thin sediment (Fig. 5.6 – 5.7, and 5.10), sparsely populated areas will be infilled by new growth (Fig. 4.6 and 4.7), and *Thalassia* will renew its advance over the Bare Sand Zone.

The effects of storms may also account for other characteristics of Frank Sound and Pease Bay biota. 1) *Thalassia* leaf count is low and leaf length is relatively short. Frank Sound and Pease Bay *Thalassia* communities are more comparable to the stressed transitional area between the reef shoal (Bare Sand Zone) and the richer grass plain described in North Sound (Raymont *et al.*, 1976). 2) Deposits of leaf detritus on the lagoon floor are largely absent or limited in thickness. 3) Noticeably absent from Frank Sound and Pease Bay is the sea star, *Oreaster reticulatus*, which is common in North Sound. Sponge, tunicates, and sea cucumbers (*Holothuria mexicans*) are rare compared with the numbers and varieties found in North Sound. The underdeveloped *Thalassia* community, lack of debris, and lower species diversity of Frank Sound and Pease Bay could all be explained by storms that periodically stress the environment and flush the lagoons with high speed currents.

Another important observation concerning the impact of storms is the low mud and silt content in Frank Sound and Pease Bay. Previous studies have emphasized the high silt and mud contents associated with dense *Thalassia*. The life cycle of *Thalassia* is short, resulting in several generations per year that can produce significant volumes of epibiont sediment in the silt and clay size range (Stockman *et al.*, 1967; Land, 1970; Patriquin, 1975; Nelsen and Ginsburg, 1986). The rates of annual epibiont production was estimated at 118 ± 44 g/m²/yr for Florida Bay *Thalassia* banks (Nelsen and Ginsburg, 1986). Sea grass also has a dampening affect on current that increases the deposition of fine–grain sediment (Wayne, 1974; Ward *et al.*, 1984; Almasi *et al.*, 1987). Almasi *et al.* (1987) found baffling–enhanced sedimentation rates in grass areas on the east coast of Florida, 1.8 and 1.2 times that of the grass free areas during the summer and winter, respectively. Clearly the lack of silt and clay in Frank Sound and Pease Bay points to the importance of storms in removing fines. This effect is likely enhanced by infanal resuspension and removal by fair–weather currents.

C. CONCLUSIONS

The effects of severe storm and hurricane waves and currents are far more intense and greatly exceed the effects of fair–weather processes in Frank Sound and Pease Bay. No part of these lagoons escape the effects of these storm processes.

1) Under fair–weather conditions sediment production, bioerosion, bioturbation, and *Thalassia* colonization are the dominant processes. Although fair–weather lagoon circulation is great enough to keep water temperature, salinity, and turbidity close to open ocean levels, fair–weather currents are not strong enough to account for the distribution of sediment or biota.

2) Variation in sediment grain–size and biota enables three reef–parallel zones to be distinguished: the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones. One additional substrate, the Bare Rock Zone, is generated in areas affected by storm erosion.

3) The three reef–parallel zones are controlled by depositional processes during hurricanes. At the height of a hurricane, waves and currents carrying sediment from the fore–reef and shelf environments readily overtop the reef crest. Once in the lagoons current energy is lost due to frictional attenuation and the water looses its capacity to transport sediment resulting in deposition. The coarsest material is deposited near the reef crest and the finer sediment is transported to near shore, at least 500 – 600 m from the reef crest. These sediments are consistently poorly sorted and have a unimodal grain–size distribution indicating a rapid depositional event that affects all parts of the lagoon.

4) The Bare Rock Zone results from storm erosion. At the height of the storms, some wave energy passes over the reef crest and is not broken until it reaches the shore. Shore–parallel bare rock is found where near shore bedrock is < 1.5 – 2.0 m below sea level. This is probably the level that these secondary breakers are able to strip sediment and rip up *Thalassia*. As the storm passes, wind driven currents and wave overtopping of the reef decrease, allowing the water that has piled in the lagoons to drain in topographically controlled mega–rip currents. Areas near these channels are similarly stripped of sediment and *Thalassia*.

5) Bedrock topography appears to be small scale surface karst similar in relief to present day Grand Cayman. The thickest sediment is found filling bedrock depressions. Sediment covers bedrock to a level of 1.5 – 2.0 m below sea level, accept in areas stripped by hurricane currents.

6) Hurricanes also control of the distribution of major biological communities. Brown algae and coral communities colonize the hurricane deposited back–reef rubble of the Rubble and Knob Zone. Whereas, the Bare Sand Zone, an area subjected to periodic intense storm agitation, is only colonized by transient green algae and sparse *Thalassia*. The *Thalassia* and Sand Zone supports a more dense *Thalassia* community because it is far enough from the reef crest (~ 300 m) that storm currents are reduced and the *Thalassia* is able to resist storm energy. *Thalassia* colonization rapidly advances into the Bare Sand Zone during quiescent periods only to be ripped up during storms.

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VIII. APPENDICES

Appendix A: Conspicuous Fauna of Frank Sound and Pease Bay

This is not intended to be a complete catalogue of lagoon fauna but rather a listing of the prominent and common types of fauna and species encountered. Fish are not included.

Phylum: Cnidarians
Class: Anthozoa
Order: Scleractinia
(Stony Corals)

Species\Environment	*Thalassia* and Sand Zone	Bare Sand Zone	Bare Rock Zone	Coral Knolls	Rubble and Knob Zone	Reef Crest Area
Acropora cervicornis					x	
Acropora palmata						x
Acropora prolifera					x	
Agaricia agaricites			x	x	x	x
Agaricia fragilis				x	x	
Colpophyllia natans					x	x
Dichocoenia stokesi				x	x	x
Diploria clivosa				x	x	x
Diploria labyrinthiformis				x	x	x
Diploria strigosa				x	x	x
Favia fragum			x	x	x	x
Montastrea annularis			x	x	x	x
Montastrea cavernosa				x	x	x
Porites astreoides			x	x	x	x
Porites divaricata	x	x	x			
Porites porites			x	x	x	x
Siderastrea radians	x	x	x		x	x
Siderastrea siderea				x	x	x
*Eusmilia fastigiata**				x	x	
*Isophyllastrea rigida**					x	x
*Isophyllastrea sinuosa**					x	x
*Madracis decactis**					x	
*Manicina areolata**				x	x	
*Meandrina meandrites**					x	x
*Mussa angulosa**					x	
*Stephanocoenia michelini**					x	

* denotes rare or very rare varieties.

Appendix A: continued

Phylum: Cnidarians
Class: Anthozoa
Order: Actiniaria
(Anemones)
- various spec' .. including

Species\Environment	*Thalassia* and Sand Zone	Bare Sand Zone	Bare Rock Zone	Coral Knoll	Rubble and Knob Zone
Condylactis gigantea			x	x	x
Bartholomea annulata			x	x	x

Phylum: Cnidarians
Class: Anthozoa
Order: Gorgonacea
(Gorgonians)
- various species including

Species\Environment	*Thalassia* and Sand Zone	Bare Sand Zone	Bare Rock Zone	Coral Knoll	Rubble and Knob Zone	Reef Crest Area
Plexaura homomalla			x	x	x	x
Plexaura flexuosa			x	x	x	x

Phylum: Cnidarians
Class: Hydrozoa
Order: Millepora
(Hydrocorals)
- various species including

Species\Environment	*Thalassia* and Sand Zone	Bare Sand Zone	Bare Rock Zone	Coral Knoll	Rubble and Knob Zone	Reef Crest Area
Millepora alcicornis			x	x		
Millepora complanata			x	x	x	x
MIllepora squarrosa					x	x

Appendix A: continued

Phylum: Cnidarians
Class: Hydrozoa
Order: Hydroida
(Hydroids)
- diverse and numerous but not identified

Phylum: Cnidarians
Class: Hydrozoa
Order: Scyphozoa
(Jellyfish)
- present but not identified

Phylum: Porifera
Class: Demospongiae
(Sponges)
- present but not identified
- five species identified and an additional thirteen found but not identified in North Sound (Raymont *et al.*, 1976)

Phylum: Chordata
Subphylum: Urochordata
Class: Ascidiacea
(Tunicates)
- present but not identified

Phylum: Ctenophora
Class: Tentaculata
(Comb Jellies)
- present but not identified

Phylum: Platyhelminthes
Class: Tubellaria
Order: Polycladida
(Flatworms)
- various species including *Pseudoceros bicolor* (living on *Thalassia* leaves)

Phylum: Annelida
Class: Polychaeta
(Segmented Worms)
- various species of 'Fire Worms' (Subclass Errantia, Family Amphinomidae),Calcarious Tube Worms (Subclass Sedentaria, Family Serpulidae), and 'Feather Duster Worms' (Subclass Sedentaria, Family Sabellidae)
- the latter group includes
Sabellastarte magnifica
Bispira brunnea
Bispira variegata
Anamobaea sp.
Arenicola cristata

Phylum: Arthropoda
Class: Crustacea
(Crustaceans)
- diverse and numerous but not identified; common ones include:
Callianassa sp. (Ghost Shrimp)
Panulirus argus (Spiny Lobster)
Petrochirus diogenes (Giant Hermit)
Calcinus tibicen (Orangeclaw Hermit)
Callinectes sp. (Blue Crabs)
- seventy-nine species identified and an additional forty-five found but not identified in North Sound; eight species identified and five unidentified in South Sound (Raymont *et al.*, 1976)

Phylum: Ectoprocta
Class: Gymnolaemata
(Bryzoans)
- present but not identified
- three species identified in North Sound (Raymont *et al.*. 1976)

Phylum: Mollusca
Class: Gastropoda
Subclass: Prosobranchia
(Snails)
- various species including
Strombus gigas
Strombus costatus
Fasciolaria tulipa
Oliva sp.
Cerithium sp. (Litteratum?)
Bulla striata
- fifty species identified[1] and an additional twenty-six found but not identified in North Sound (Raymont *et al.*, 1976)

Phylum: Mollusca
Class: Gastropoda
Subclass: Opisthobranchia
('Slugs')
- various species including
Cyphoma gibbosum
Elysia sp.

Phylum: Mollusca
Class: Amphineura
(Chitons)
Acanthopleura granulata

Phylum: Mollusca
Class: Bivalvia
(Bivalves)
- various species including
Pinctada radiata
Pinna carnea
Tellina radiata
Isognomon alatus
Lima pellucida
- thirty-three species identified and an additional six found but not identified in North Sound (Raymont *et al.*, 1976)

Phylum: Mollusca
Class: Cephalopoda
(Squid/Octopuses)
- various species including
Doryteuthis sp. (Inshore Arrow Squid)
Octopus vulgaris (Common Octopus)
- three species identified in North Sound (Raymont *et al.*, 1976)

Phylum: Echinodermata
Class: Asteroidea
(Sea Stars)
- various species including
Luidia clathrara
- twenty-six species identified[2] and an additional nine found but not identified in North Sound (Raymont *et al.*, 1976)

Phylum: Echinodermata
Class: Ophiuroidea
(Brittle Stars)
- various species including
Ophionereis reticulata
Ophiothrix suensonii
Ophiocoma echinata

Phylum: Echinodermata
Class: Echinoidea
(Sea Urchins)
- various species including
Diadema antillarum
Diadema lucunter
Lytechinus variegatus
Tripneustes ventricosus
Clypeaster subdepressus

Phylum: Echinodermata
Class: Holothuroidea
(Sea Cucumbers)
Holothuria mexicans

[1] This count includes all both Gastopoda prosobranchia and opisthobranchia.

[2] This count includes all Echinodermata.

Appendix B: Conspicuous Flora Frank Sound and Pease Bay

This is by no means intended to be a complete catalogue of lagoon flora but rather a listing of the prominent and common species encountered.

Phylum: Angiospermae
Class: Angiospermae
(Flowering Plants)
Thalassia testudinum
Syringodium filiforme
Halophilia baillonis

Phylum: Phaeophyta
(Green Algae)
- various species including
Halimeda incrassata
Halimeda monile
Halimeda opuntia
Halimeda tuna
Penicillus dumetosus
Penicillus pyriformis
Penicillus capitatus
Udotea flabellum
Udotea cyathiformis
Acetabularia calyculus
Acetabularia crenulata
Avrainvillea nigricans
Avrainvillea longicaulis
Caulerpa cupressoides
Caulerpa sertulariodes
Caulerpa prolifera
- 'Sea Pearl', 'film' or 'sheet-like', 'net-like', and filimentous green algae varieties present but not identified
- present but not identified

Phylum: Phaeophyta
(Brown Algae)
- various species including
Padina sp.
Dictyota sp.
Stypopdium zonale
Turbinaria sp.
Sargassum sp.

Phylum: Phaeophyta
(Red Algae)
- copious varieties including
Amphiroa sp. (Twig Alga)
Jania adherens
Galaxaura sp. (Thicket Alga)
Acanthophora spicifera
Champia sp.
- 'Reef Cement' and crustose red algae varieties present but not identified

Appendix C: Survey of the conspicuous Bare Sand Zone biota of Frank Sound

Survey of biota found in randomly placed 1 x 1 m grids at three localities in Frank Sound (Fig. 2.1). Counts represent blades/m^2 for *Thalassia* and *Syringodium* and individuals/m^2 for other biota.

Species	East Frank Sound (30 sites)																													
Thalassia testudinum	0	0	0	100	39	16	0	74	5	145	60	800	24	0	0	975	0	70	0	52	5	270	0	110	70	68	36	30	80	0
Syringodium filiforme	37	0	0	34	1	72	6	46	48	21	92	44	0	0	0	300	0	58	0	63	77	60	0	66	126	25	0	80	70	0
Halimeda monile	0	0	0	13	3	2	0	0	6	0	0	0	0	0	0	2	0	3	0	2	0	0	0	0	1	0	0	1	0	0
Halimeda incrassata	0	0	0	0	0	1	0	0	0	0	0	0	2	3	0	6	4	10	0	3	0	6	0	0	0	1	0	0	10	3
Penicillus spp.	0	2	4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Avrainvillea spp.	9	0	0	4	1	0	0	0	0	0	0	2	0	0	0	0	0	12	0	6	0	2	0	0	0	0	0	10	0	0
Udotea spp.	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	2	1	2	1	0	0	0	0	0	0	1	1	3	0	0
Caulerpa cupressoides	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	12	28	13	0	0	0	0	0	0	5	0	0
Acetabularia spp.	7	4	8	9	9	7	27	24	3	10	13	30	3	1	2	5	2	2	0	0	3	7	0	9	4	3	6	10	10	3
Strombus gigas	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Species	West Frank Sound (28 sites)																											
Thalassia testudinum	10	19	8	28	0	8	49	86	20	72	8	4	17	30	18	50	110	54	39	22	4	34	0	0	0	0	0	0
Syringodium filiforme	60	86	52	98	43	42	31	120	46	59	54	86	54	56	35	60	130	60	85	21	12	35	80	30	80	50	11	9
Halimeda monile	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	0	2	0	0	1	5
Halimeda incrassata	0	0	0	0	0	0	0	25	2	0	0	0	0	2	1	0	0	0	0	0	3	2	14	4	11	12	1	7
Penicillus spp.	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Avrainvillea spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Udotea spp.	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Caulerpa cupressoides	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acetabularia spp.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Strombus gigas	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix C: continued

Species	East of Frank Sound Channel (31 sites)															
Thalassia testudinum	24	34	160	12	86	84	100	60	0	0	20	48	0	0	20	0
Syringodium filiforme	92	54	124	45	220	50	116	84	0	66	160	58	36	13	70	80
Halimeda monile	3	0	3	0	2	0	7	1	0	5	5	0	0	8	4	0
Halimeda incrassata	0	1	0	19	2	0	2	9	3	1	10	0	16	2	8	0
Penicillus spp.	0	0	1	0	2	2	3	0	0	0	0	0	0	4	0	0
Avrainvillea spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Udotea spp.	0	0	1	2	0	0	0	0	0	2	0	0	0	0	0	0
Caulerpa cupressoides	0	0	1	1	0	0	0	13	0	0	0	0	9	0	0	0
Acetabularia spp.	4	2	2	1	2	8	3	0	12	0	0	4	1	4	0	0
Strombus gigas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassia testudinum	0	30	20	0	0	38	5	14	2	73	0	12	5	0	15	
Syringodium filiforme	66	130	33	0	110	100	23	35	5	11	35	41	12	0	60	
Halimeda monile	0	2	1	0	0	3	0	0	4	0	2	3	0	5	2	
Halimeda incrassata	4	3	0	0	1	2	1	0	1	0	11	0	0	0	0	
Penicillus spp.	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	
Avrainvillea spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Udotea spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Caulerpa cupressoides	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	
Acetabularia spp.	2	3	0	0	0	3	0	0	0	0	0	0	0	0	3	
Strombus gigas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Appendix D: Survey of the conspicuous *Thalassia* and Sand Zone biota of Frank Sound

Survey of biota found in randomly placed 1 x 1 m grids at two localities in Frank Sound (Fig. 2.1). Counts represent blades/m^2 for *Thalassia* and *Syringodium* and individuals/m^2 for other biota.

Species	West Frank Sound (20 sites)																			
Thalassia testudinum	175	175	575	425	300	800	250	175	350	275	200	200	225	250	300	225	175	400	225	175
Syringodium filiforme	100	50	0	0	0	0	0	0	0	0	50	0	0	50	50	25	100	0	75	50
Halimeda monile	0	0	2	0	0	0	8	14	20	11	0	0	0	0	0	0	0	0	0	0
Halimeda incrassata	1	1	0	0	5	20	20	0	8	11	40	2	0	0	6	0	9	28	6	4
Penicillus spp.	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Avrainvillea spp.	0	0	0	0	0	2	0	1	1	2	0	0	0	0	0	0	0	0	0	0
Shrimp Mounds	0	1	2	2	1	4	2	0	0	1	0	2	1	0	3	1	0	0	1	1

Species	East Frank Sound (7 sites)						
Thalassia testudinum	1000	925	475	500	375	425	575
Syringodium filiforme	50	175	50	50	125	200	25
Halimeda monile	0	0	0	0	0	0	0
Halimeda incrassata	1	0	0	0	16	5	0
Penicillus spp.	0	0	0	0	0	0	0
Avrainvillea spp.	0	0	0	0	0	0	0
Shrimp Mounds	0	0	0	0	0	0	0

Appendix E: Grain-size analysis data

Grain–size analysis statistics were calculated using the formulas of Folk and Ward (1957). Percentiles were determined from hand–ploted cumulative weight percent curves on probability graphs.

Beach

Sample #	Median	Mean	Sorting	Skewness
FS-1 0m	0.64	0.63	0.92	0.53
FS-5 0m	0.80	0.90	0.80	1.89
FS-3 0m	1.27	1.23	0.73	-0.11
FS-2 0m	1.82	1.72	0.93	-1.40
PB-1 0m	2.58	2.50	0.62	-0.72
PB-2 0m	1.98	1.82	1.01	-2.67
PB-8 0m	2.38	2.31	0.46	-0.55
PB-6 0m	1.71	1.77	0.82	-0.08
PB-5 0m	-0.10	-0.06	0.45	0.21

Thalassia and Sand Zone

Sample #	Median	Mean	Sorting	Skewness
FS-1 90m	2.53	2.42	1.33	-1.40
FS-1 150m	1.36	1.36	1.25	-0.77
FS-1 180m	1.08	1.00	0.88	-0.86
FS-5 480m	2.25	2.08	1.07	-0.74
FS-5 570m*	2.41	2.24	1.05	-0.87
FS-3 300m	2.83	2.69	1.13	-1.98
FS-3 600m*	2.94	2.80	1.04	-3.08
FS-2 60m	1.56	1.51	0.85	-0.68
FS-2 150m	0.84	0.90	0.79	0.61
PB-1 60m	1.52	1.45	1.37	-0.47
PB-2 240m**	2.67	2.39	1.69	-2.75
PB-8 60m	1.69	1.62	1.31	-0.50
PB-8 270m**	2.64	2.33	1.50	-4.83
PB-6 30m	0.80	0.69	1.12	-2.90
PB-6 60m***	0.47	0.36	1.05	-0.92
PB-5 20m	0.88	1.03	1.21	1.49

* Transitional Zone

** Thalassia bank near reef

*** near shore Bare Rock Zone

Inner Thalassia and Sand Zone and near shore Bare Rock Zone (central Frank Sound)

Sample #	Median	Mean	Sorting	Skewness
FS-5 30m	1.88	2.84	3.50	35.11
FS-5 90m	2.33	2.25	1.23	-0.32
FS-5 150m	2.13	2.11	1.25	0.94
FS-3 30m	2.52	2.83	2.35	18.26
FS-3 90m	2.60	2.84	2.48	16.95
FS-3 120m	1.93	2.12	1.72	3.81

Bare Sand Zone

Sample #	Median	Mean	Sorting	Skewness
FS-1 210m	1.20	1.04	1.01	-1.47
FS-1 240m	1.07	0.89	1.06	-2.33
FS-1 270m	1.00	0.93	0.94	-1.09
FS-1 300m	1.54	1.34	1.12	-2.73
FS-1 330m	1.80	1.63	0.94	-2.40
FS-1 360m	1.53	1.35	1.23	-2.96
FS-1 390m	1.10	0.93	1.12	-1.92
FS-1 420m	1.76	1.46	1.28	-4.87
FS-1 450m	1.42	1.26	1.10	-2.54
FS-1 480m	1.19	0.99	1.19	-3.34
FS-5 690m	2.47	2.27	1.08	-2.57
FS-5 780m	2.20	1.97	1.24	-3.28
FS-3 690m	2.85	2.73	0.93	-2.66
FS-3 780m^	1.56	1.34	1.42	-3.77
FS-2 270m	2.02	1.86	0.90	-2.79
FS-2 330m^	1.32	1.13	1.38	-3.13
PB-1 120m	1.77	1.50	1.20	-4.36
PB-1 160m^^	2.03	1.74	1.36	-5.26
PB-2 120m	2.84	2.59	1.16	-3.27
PB-8 120m	2.97	2.84	0.95	-2.70
PB-8 180m	2.64	2.28	1.22	-3.94
PB-6 120m^^	1.92	1.76	0.93	-2.56
PB-6 180m	2.50	2.21	1.16	-4.00
PB-6 270m	1.48	1.30	1.41	-3.03
PB-6 390m^	1.19	1.13	1.52	-3.94
PB-5 80m^	-0.07	-0.23	1.80	-3.56

^ Transitional Bare Sand to Rubble and Knob Zone

^^ near coral knoll

Appendix E: contir.·ued

Rubble and Knob Zone

Sample #	Median	Mean	Sorting	Skewness
FS-1 510m	0.75	0.43	1.70	-7.87
FS-1 540m	1.08	0.50	2.32	-16.01
FS-1 570m	-3.87	-3.14	2.10	18.01
FS-1 600m	-2.60	-2.00	2.14	12.16
FS-5 930m	n/a	n/a	n/a	n/a
FS-3 870m	n/a	n/a	n/a	n/a
FS-2 420m	n/a	n/a	n/a	n/a
PB-1 240m~	0.10	-0.55	2.29	-12.66
PB-2 320m	0.60	0.28	1.95	-10.02
PB-8 330m	0.80	1.00	2.09	-1.66
PB-8 390m	0.42	-0.17	1.76	-7.39
PB-6 450m	-0.38	-0.96	2.72	-14.09
PB-5 140m	n/a	n/a	n/a	n/a

~ Rubble cemented into a rock surface

*n/a: see p. 72

Soft Sediment Cores

Sample #	Median	Mean	Sorting	Skewness
SCFSa 0cm	1.97	1.92	1.02	1.10
SCFSa 20cm	2.03	1.96	1.11	0.94
SCFSa 30cm	2.07	1.98	1.07	0.61
SCFSa 40cm	1.87	1.61	1.46	-4.17
SCFSa 50cm	2.10	1.91	1.14	-1.85
SCFSd 0cm	2.17	1.97	1.02	-2.66
SCFSd 20cm	1.93	1.68	1.18	-3.71
SCFSd 40cm	2.32	2.12	1.06	-2.85
SCFSd 60cm	2.40	2.27	0.98	-2.06
SCFSd 77cm	2.30	2.16	0.98	-1.62
SCFSf 0cm	2.46	2.34	0.77	-1.34
SCFSf 20cm	2.36	2.21	1.00	-2.08
SCFSf 40cm	2.40	2.33	1.01	-1.45
SCFSf 60cm	2.29	2.21	0.90	-1.21
SCFSf 80cm	2.28	2.21	0.86	-1.00
SCFSf 100cm	2.28	2.16	0.95	-1.35
SCFSf 120cm	2.28	2.21	0.89	-0.79
SCFSf 134cm	2.33	2.28	0.95	-0.71