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SEDIMENTOLOGY OF A CURRENT-DOMINANTED LAGOON:

CASE STUDY OF SOUTH SOUND, GRAND CAYMAN, B. W. I.

by

JENNIFER M. R. BEANISH

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

DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Sedimentology of a Current-Dominated Lagoon: Case Study of South Sound, Grand Cayman, B. W. I. submitted by Jennifer M. R. Beanish in partial fulfillment of the requirements for the degree of Master of Science.

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4 April 2000

ABSTRACT

South Sound, a 3.4 km^2, shallow (< 2 m), shoreline-parallel, funnel-shaped lagoon, is located on the southwest exposed windward margin of Grand Cayman. The facies, which are defined by biota, grain-size, sorting and skewness are: *Thalassia*, Sand, Rock Bottom, Brown Algae, Rubble, and Coral Head. Between 1971 and 1992, the *Thalassia* Facies expanded in area by 17.3%, mostly at the expense of the Sand Facies.

Under fair-weather conditions, sediment production, bioturbation, and *Thalassia* colonization dominate. The northeast trade winds and lagoonal geometry and orientation, however, induce currents almost everyday that increase in magnitude from east to west. These currents rework and redistribute the sediments to produce accumulations that are thick and fine-grained in the east and close to shore, and sporadic and coarse-grained in the west. Hurricanes enhance the effects of everyday currents, but their force is concentrated on the reef crest. Coral fragments (dominantly *Acropora palmata*) broken from the reef crest produce a concentrated rubble belt directly behind the reef. Areas of *Thalassia* are ripped-up by storms, but are maintained grass-free by everyday currents.

To my sisters.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

A lagoon is a shallow body of water, typically less than 10 m deep, which is partially or completely separated from the open ocean by a barrier, usually a reef. Lagoons are predominantly areas of low water energy, controlled by *in situ* carbonate sediment production as marine biota disintegrate. The resulting sediments are fine-grained and polymodal, because the grain size is determined by biotic type. When currents are weak, bioturbation is extensive, and faunal diversity is low. Lagoons are isolated from the prevalent open ocean conditions and processes, but are still influenced by them, creating a unique environment. The quiet-water *in situ* sediment production is commonly modified by higher energy, intensity-varying currents and storms. Many of the fines are winnowed from the sediment, leaving a sand-sized, unimodal carbonate sediment. Sorting will reflect the changes in energy. The currents and waves will control the distribution of sediments in the lagoon.

South Sound, Grand Cayman, although influenced by both fair-weather sediment production and storms, is a current-dominated lagoon. The reef surrounding South Sound attenuates the deep water waves, converting the wave energy into currents as they enter the lagoon. Previous studies used sophisticated wave, wind, and current measuring devices to quantify their speeds and directions in and surrounding South Sound (Roberts *et al.* 1975; Darbyshire *et al.* 1976; Murray *et al.* 1977; Suhayda and Roberts 1977; Roberts 1983). Evidence of currents being the dominant process in South Sound and the implications exists in the sediments. Data on grain-size, sorting, composition, biotic density and diversity, facies distribution, and the migration of facies over time are used for the interpretation of processes in South Sound.

STUDY AREA

1.2 PHYSIOGRAPHY OF GRAND CAYMAN

Grand Cayman, Little Cayman, and Cayman Brac are located between 19°15'N - 19°45'N and 75°44'W - 81°27'W. Grand Cayman, which is the largest of the three Cayman Islands, is situated in the western Caribbean Sea, about 300 km south of Cuba and 280 km northwest of Jamaica (Fig. 1.1). Grand Cayman is 35 km long and up to 14 km wide, with a total area of 197 km^2 (Fig. 1.2). Its irregular outline is due to the presence of North Sound, a large lagoon on the western part of the island. Relief is generally less than 3 m above sea level, except for a discontinuous peripheral ridge that parallels the shoreline along the south, east, and north coasts (Fig. 1.3). The maximum elevation is 18 m at "The Mountain". The island interior is low-lying, so it has a dish-like shape (Doran 1954; Giglioli 1976; Rigby and Roberts 1976; Jones and Hunter 1994). Most coasts are lined with beach ridges, storm berms, limestone terraces, or boulder ramparts (Hernandez-Avila *et al.* 1977; Woodroffe *et al.* 1983). Grand Cayman is formed of exclusively carbonate rocks. Much of the exposed rock has been karsted or phytokarsted, forming a terrain of sharp pinnacles and deep sinkholes (Folk *et al.* 1973; Jones and Smith 1988). There are no rivers on the island. Mangroves in peaty swamps cover approximately 36% of Grand Cayman (Wells 1988) but palms, buttownwoods, cacti, and short scrub are also common (Proctor 1984; Brunt 1994). Coco-plum, sea-grape, mangroves, and other salt resistant shrubs and grasses vegetate the 127 kilometers of coastline (Emery 1981).

1.3 DEVELOPMENT OF REGIONAL GEOLOGY

The tectonic history of the Caribbean region is complex and many different models have been proposed to explain the present configuration of the islands (e. g., Pindell and Barrett 1990; Morris *et al.* 1990; Dillon *et al.* 1972; Sykes *et al.* 1982;

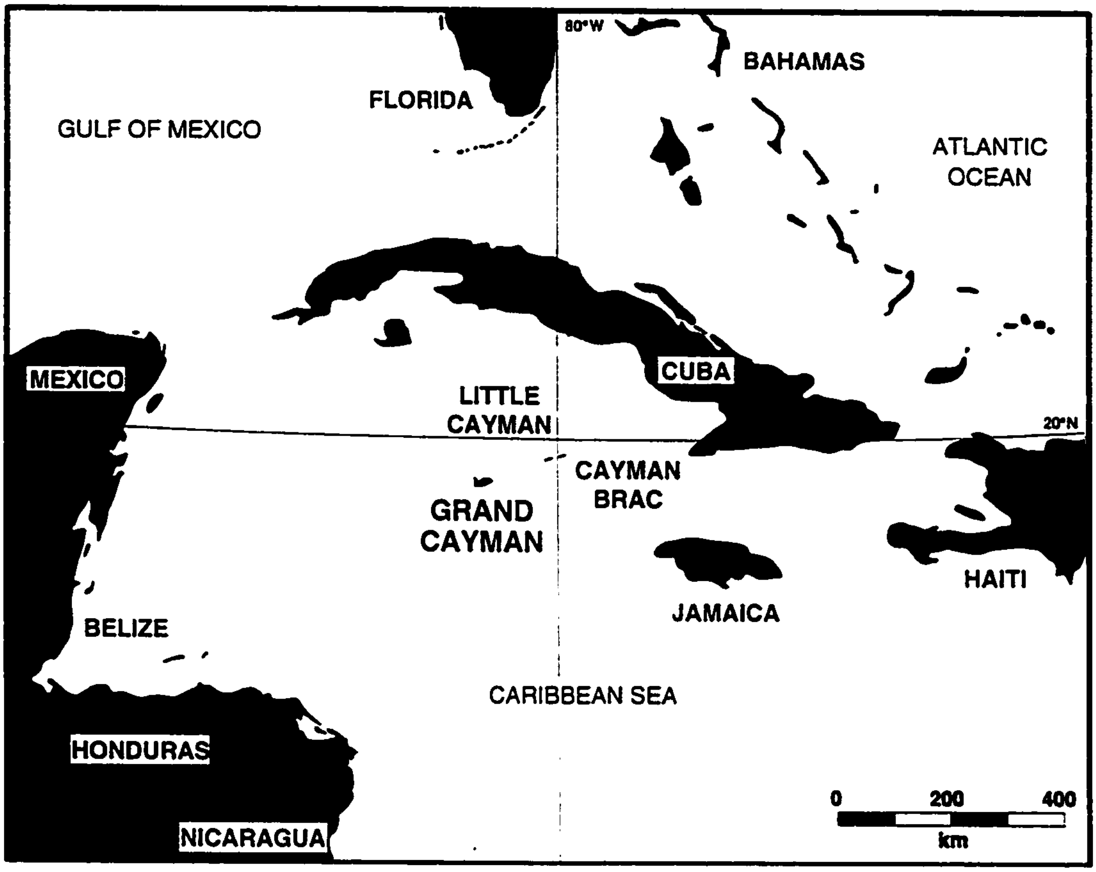

Figure 1.1. Location of Grand Cayman Island in the Caribbean Sea.

Lewis and Draper 1990). The complexity results, in part, from the fact that the Caribbean Plate must absorb the relative motions of the North American, South American, and Cocos Plates. The variable stresses on the Caribbean Plate caused the plate boundaries to evolve so that the region became composed of an agglomeration of allochthonous terranes. The Cayman Islands were on the Caribbean Plate during the pre-Cretaceous (Richards 1955), but they are presently located on the southern boundary of the North American Plate. The North American Plate is still experiencing right-lateral strike-slip motion with respect to the Caribbean Plate (Lewis and Draper 1990).

The tension produced from the eastward drift of the Caribbean Plate since the middle Tertiary contributed to the formation of the Cayman Trough (previously

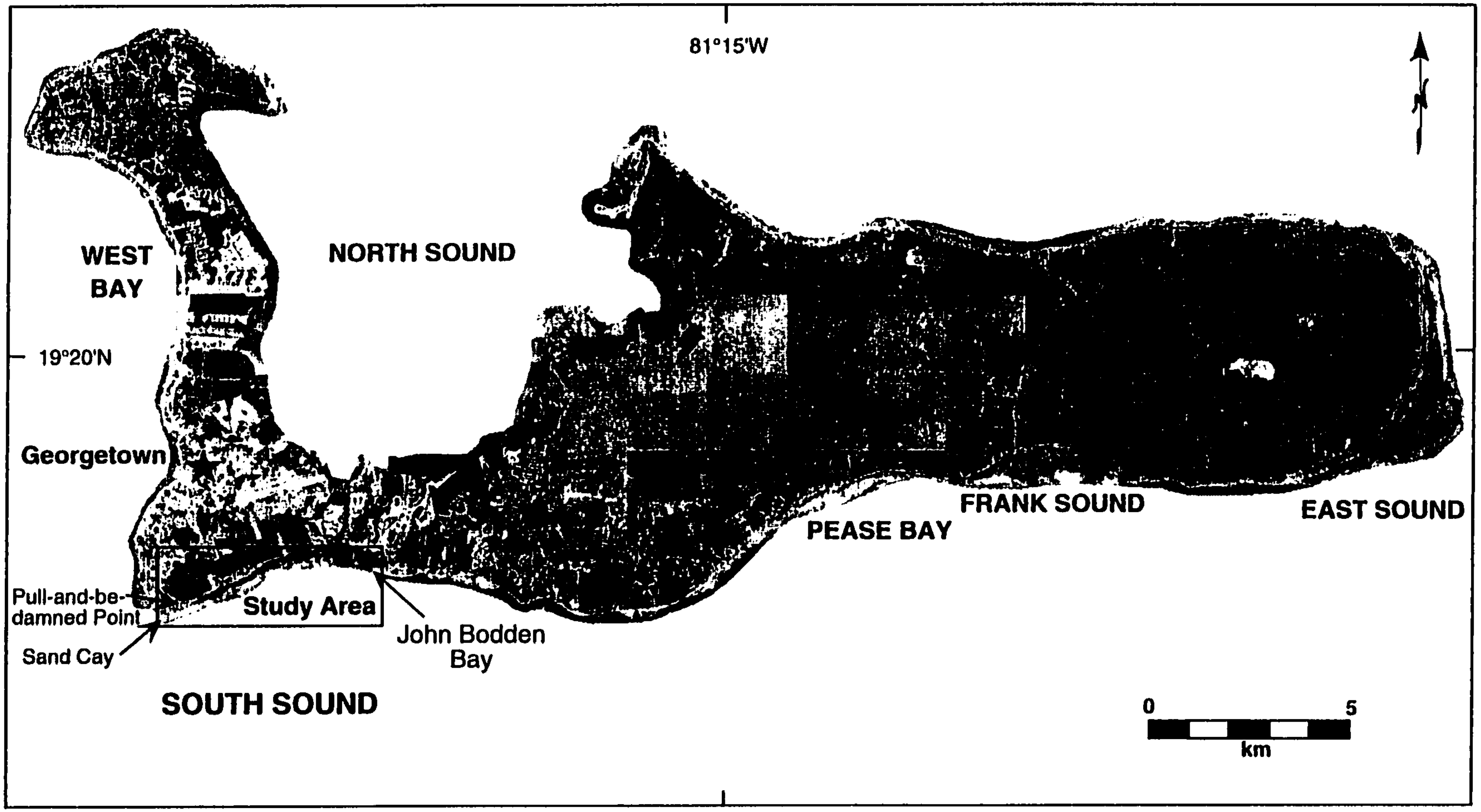

Figure 1.2. Location of South Sound on Grand Cayman. Base map provided by the Department of Lands and Survey, Government of the Cayman Islands.

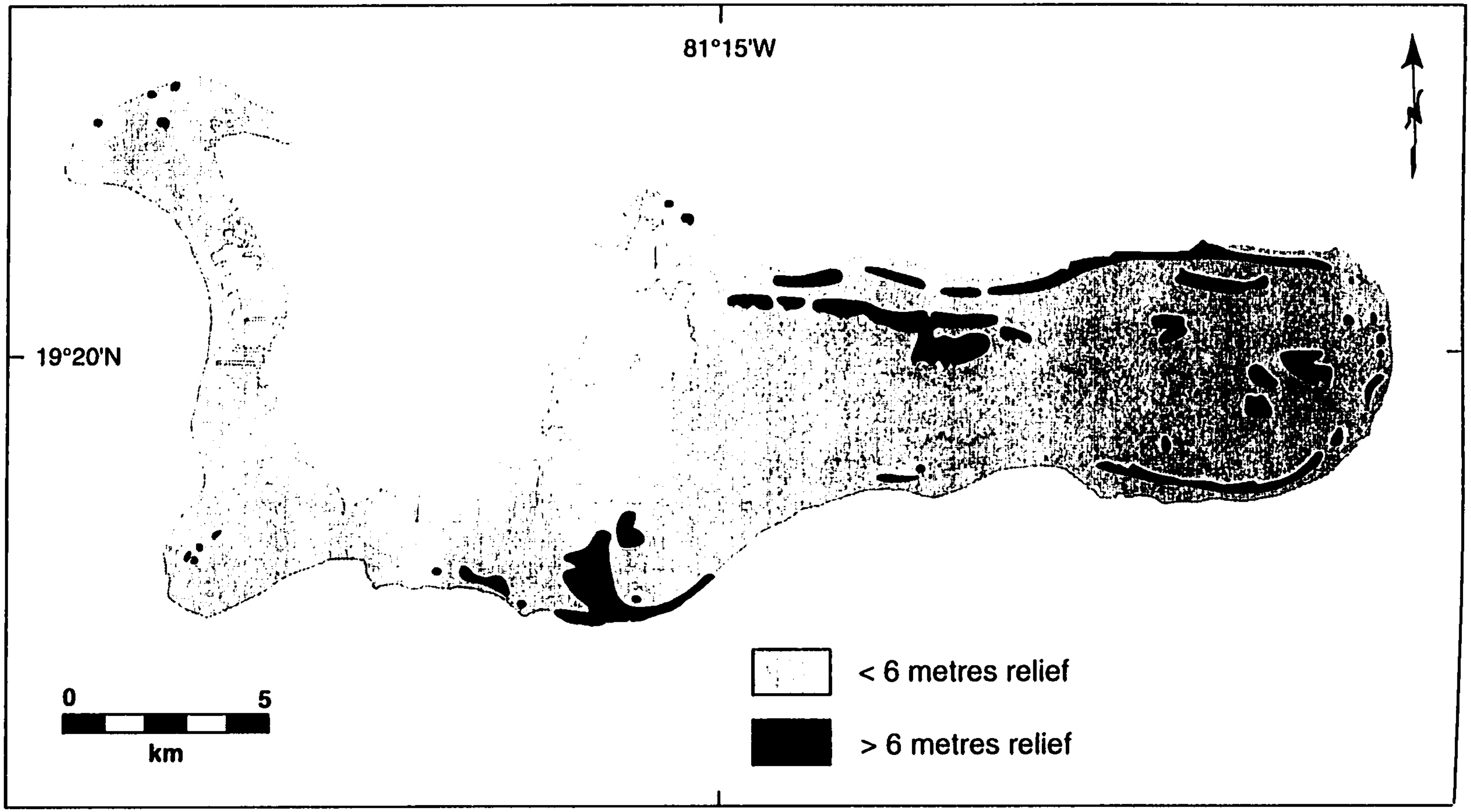

Figure 1.3. Peripheral ridges on Grand Cayman. Modified from Jones and Hunter (1994, Fig. 4).

known as the Bartlett Trough) during the Oligocene to Miocene (Brown 1968) (Fig. 1.4). The Cayman Trough is an east-northeast trending, 1200 km long extensional zone that is over 7 km deep (Case *et al.* 1990). A north-south trending spreading centre, the Mid-Cayman Ridge, at 81°40' W, has been opening at the rate of 2 cm/year, producing the thin ultramafic oceanic crustal rocks that partially form the north and south walls of the trough (Rosencrantz *et al.* 1988; Emery and Milliman 1980). Parallel to the Cayman Trough is the Oriente transform fault to the north, and the Swan transform fault to the south (Pindell and Barrett 1990). The Nicaraguan Plateau borders the faults to the south (Fig. 1.4). Varying thicknesses of terrigenous and pelagic sediments fill depressions in the Cayman Trough as a result of gravity and turbidity flows (Ladd *et al.* 1990).

The Cayman Ridge parallels the northern margin of the Cayman Trough (Fig. 1.4). This ridge developed as an island arc during an orogenic episode that took place between the late Cretaceous and Paleocene (Perfit and Heezin 1978). Although most of the ridge has subsided since the Paleocene, localized areas were uplifted as fault blocks. Each of the Cayman Islands are located on a separate fault block. The Cayman Ridge stretches from the Sierra Maestra of Cuba on its eastern-most end to the Gulf of Honduras in the west. Its flanks dip at 30°- 40° to the north and south (Fahlquist and Davies 1971). Dredging and drilling on the surface and slopes of the ridge has revealed a complex assemblage of volcanic rocks interspersed with plutonic, clastic, and shallow and deep water carbonate rocks, some of which have experienced low to medium grade metamorphism (Holcombe *et al.* 1990).

1.4 GEOLOGICAL FRAMEWORK OF GRAND CAYMAN

The carbonate rocks forming Grand Cayman have been divided into the Bluff Group and the Pleistocene Ironshore Formation (Fig. 1.5). The Bluff Group forms the core of the island, and the Ironshore Formation unconformably and discontinuously

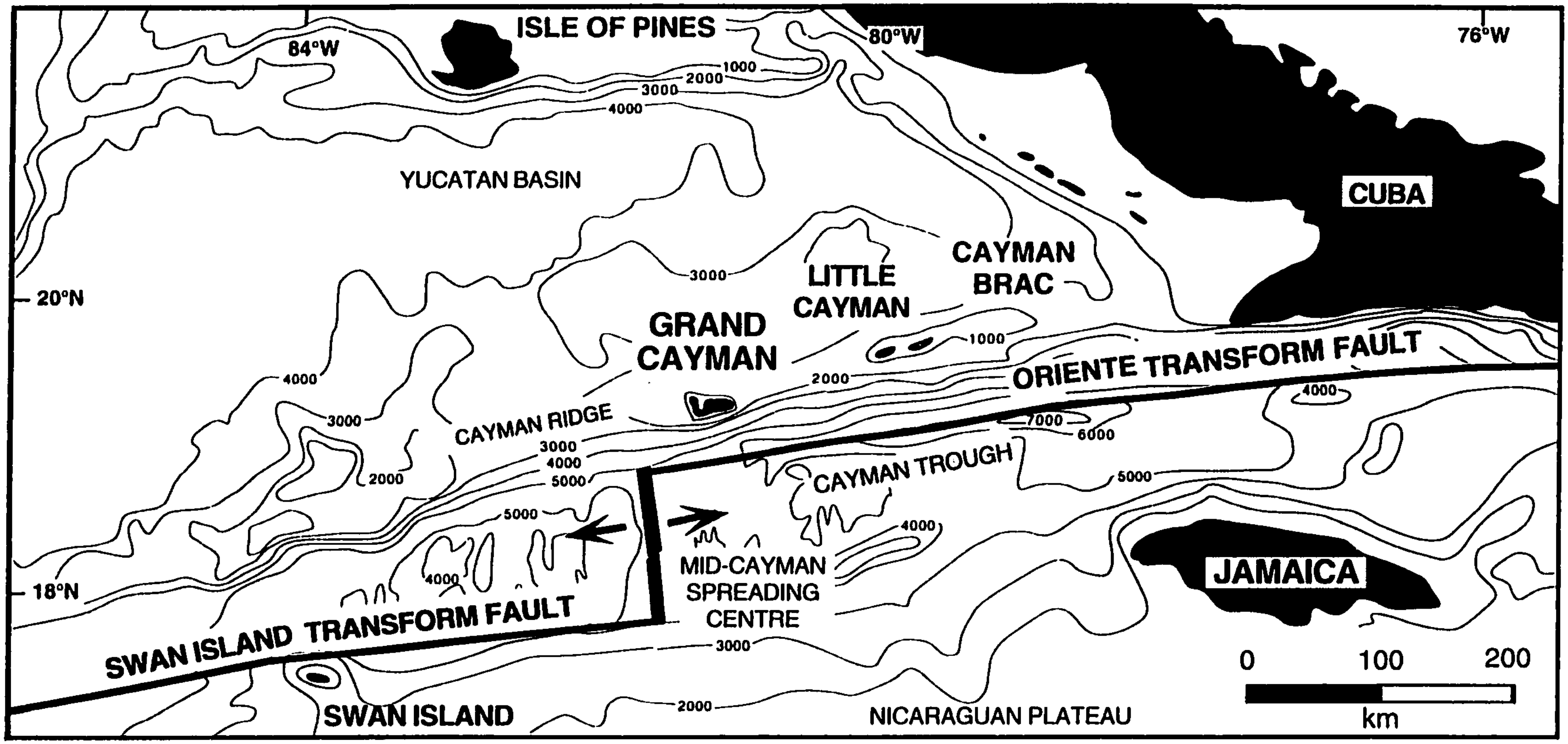

Figure 1.4. Regional tectonics of Grand Cayman. Contours are in metres. Modified from Pleydell *et al.* (1990, Fig. 1); based on information from Holcombe *et al.* (1973).

overlays it (Matley 1926; Brunt *et al.* 1973; Jones and Hunter 1989; Jones *et al.* 1994).

Matley (1926) first described the flat-lying Bluff Limestone, which he considered to be Oligocene to Miocene in age. The Bluff Limestone was later redefined as the Bluff Group by Jones *et al.* (1994) so that it could include the Brac Formation (only found on Cayman Brac), the Cayman Formation, and the Pedro Castle Formation. All three formations are separated by unconformities (Fig. 1.5). The Cayman Formation, which is at least 105 m thick, is formed of microcrystalline dolostone which has retained much of its original fabric. This formation contains numerous massive and branching corals, gastropods, bivalves, and foraminifera (Matley 1926; Jones and Hunter 1989; Jones 1992, 1994). The Pedro Castle Formation, which is softer and lighter in colour than the Cayman Formation, includes free-living corals and has less variability in cements, but more variability in lithic composition (Jones and Hunter 1989; Jones *et al.* 1994; Wignall 1995). The Bluff Group is strongly jointed and dissolution has left the rock sharply and irregularly karsted with high porosity (Mather 1972; Jones and Smith 1988).

The Ironshore Formation is a shallowing-upward sequence of reefal limestones and calcarenites (Matley 1924; Warthin 1959; Jones and Hunter 1990). Thicknesses are highly variable, but in some areas it is up to 30 m thick (Hunter and Jones 1989). The Ironshore Formation was deposited during the Pleistocene, when the low-lying areas of the island were flooded by seawater (Jones and Hunter 1990). Most deposition occurred in the Ironshore Lagoon, which covered the western half of Grand Cayman, but there are also isolated occurrences along the north, south, and east coasts (Fig. 1.5). Vézina (1997) and Vézina *et al.* (1999) divided the Ironshore Formation on the northeast corner of the island into four unconformity-bounded units, each of a different age. Other lagoonal facies have been assigned (Brunt *et al.* 1973; Hunter and Jones 1988), but these are not consistent across the island.

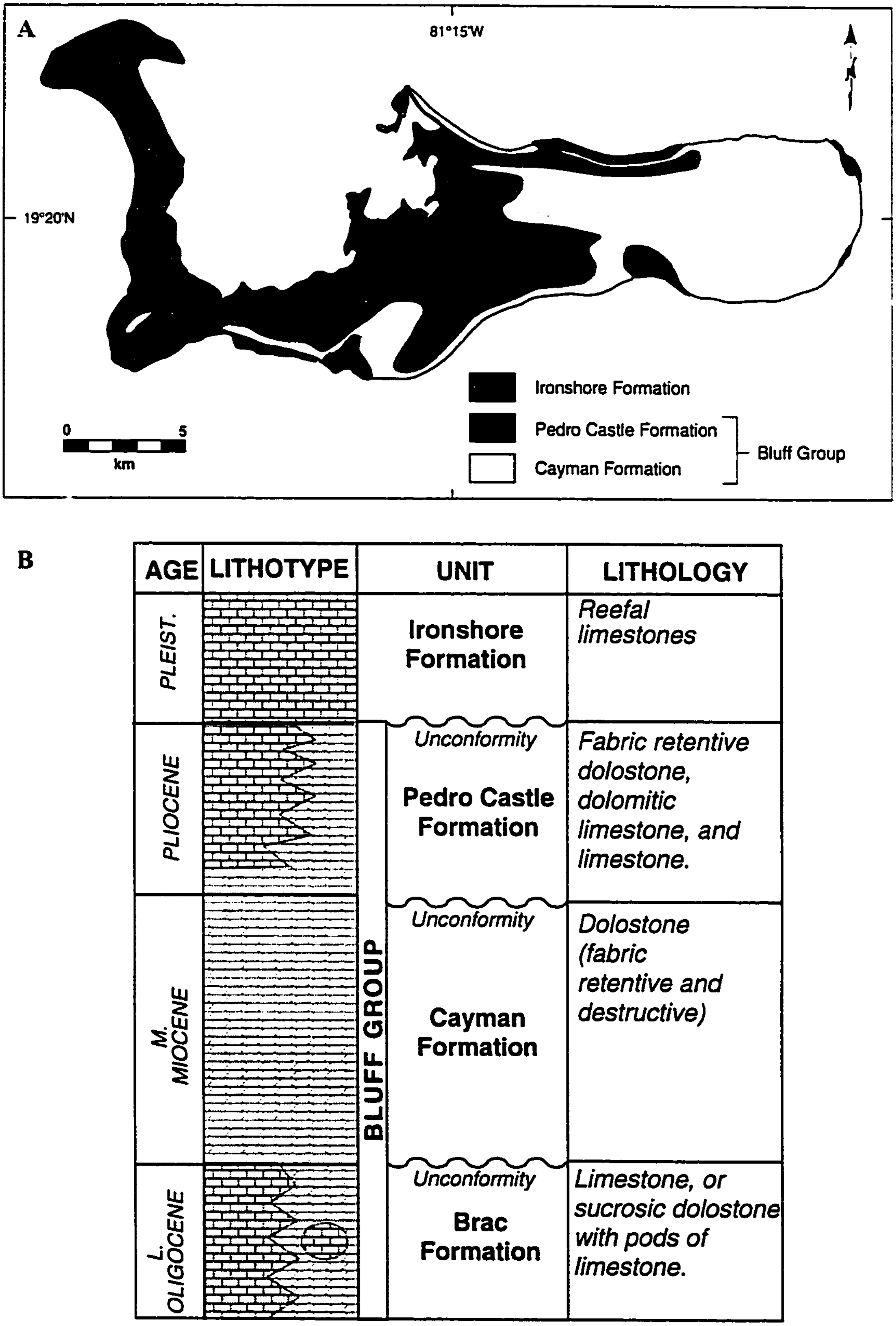

Figure 1.5. **A)** Geological framework of Grand Cayman. **B)** Stratigraphic column for the Cayman Islands. Modified from Jones *et al.* (1994) and Jones (1994).

1.5 CLIMATE

Grand Cayman has a sub-humid tropical climate with distinct seasons that are marked by changes in rainfall. During the summer, the highest temperatures are recorded in July and August with an average of 28.4°C (Fig. 1.6). The temperature drops to its average low of 24.8°C in February. The average water temperature is 29.3°C in August and 24.2°C in January (Burton 1994). Rainfall averaged 1513 mm/ year between the years of 1920 - 1987, but it is extremely variable both seasonally and geographically (Rigby and Roberts 1976; Beswick 1980; Ng 1990). The wet season is from May to November, while the winter months, December to April, are very dry (Fig. 1.6). The amount of evaporation in April exceeds rainfall by a factor of seven due to the clear skies, strong winds, and rising air temperatures. Rainfall is greatest on the western side of the island, and gradually decreases towards the east. Humidity is almost always between 65% - 100% (Burton 1994).

Winds are generally from the east, varying slightly north or south - typical of the Trade Wind Belt (Fig. 1.7). There is, however, a seasonal variation in winds, with the wind speed decreasing in summer and the direction changing during the winter. Between November and March, cold fronts passing across the mainland of North America briefly bring colder temperatures and storms along with a strong northwesterly wind (Nor'wester Gales). These produce highly agitated seas on the northern and western coasts of the island. The hurricane season is generally between August and October. Low pressure systems in the Caribbean bring hurricanes (storms with wind velocities exceeding 32 m/sec) within 10 km of the island with an average recurrence interval of about 10 (Clark 1988; Burton 1994) to 20 years (Blanchon 1995). Severe hurricanes passed over the island in 1785, 1845, 1876, 1910, and 1932 (Hirst 1910; Williams 1970; Burton 1994). The most recent hurricane to pass over the south coast of Grand Cayman was Hurricane Gilbert on September 13, 1988. Damage from this hurricane was minor.

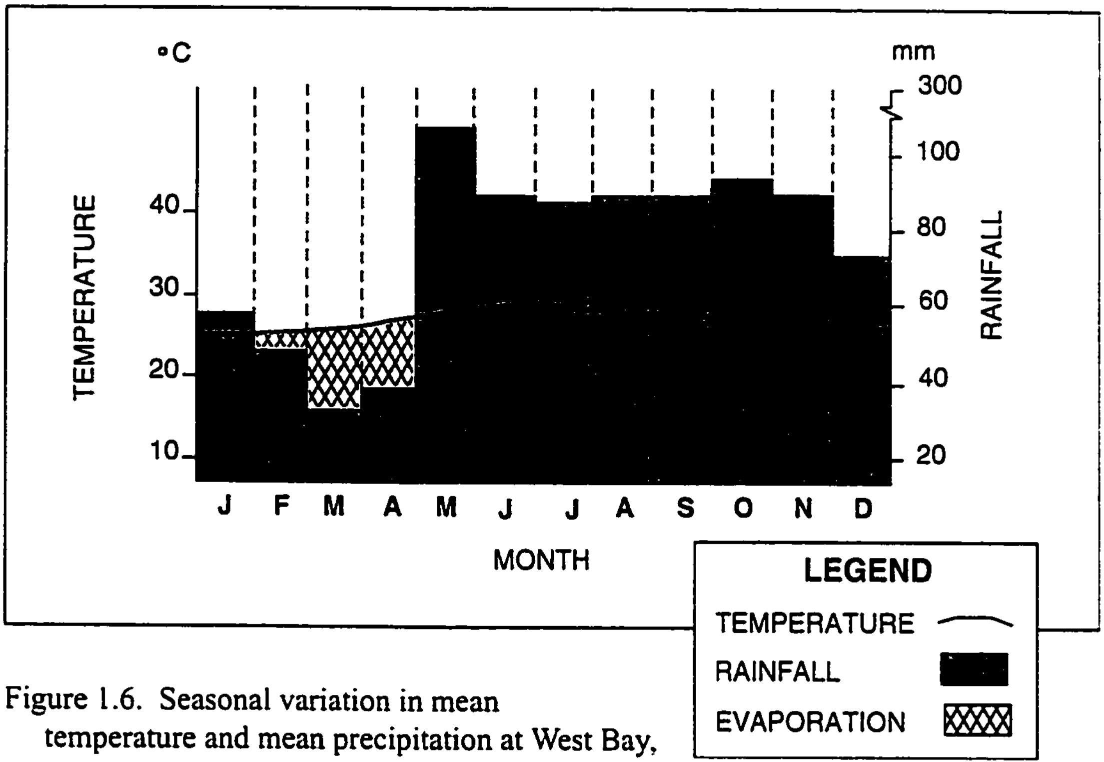

Figure 1.6. Seasonal variation in mean temperature and mean precipitation at West Bay, Grand Cayman. Temperature is based on the years 1967 - 1987 and precipitation is based on the years 1972 - 1987. Modified from Burton (1994).

1.6 Marine Hydrology

The tides affecting Grand Cayman are low-amplitude, but predominantly control the open shelf current regime. The maximum range of the semi-diurnal to mixed diurnal tides is 60 cm, with the yearly average being 35 cm (Rigby and Roberts 1976). The Mosquito Research and Control Unit (MRCU) has a permanent tidal gauge on the western side of South Sound that constantly monitors the tides. It has shown a rising trend in sea level since 1976 at a rate of about 2.4 mm/year (Burton 1994). The currents along the shelf of Grand Cayman vary in magnitude and direction with changes in the tide, but dominantly are from the southeast. The strongest currents flow westward along the north and south coasts of the island and average 50 cm/sec along the margin shelf, decreasing in strength by 65 - 75% on the shallow shelf due to friction (Fig. 1.7).

Waves, which develop in response to the Northeast Trade Wind System and storms, typically approach Grand Cayman from the northeast to southeast (Fig. 1.8). The typical trade wind speed is 6 m/sec (Suhayda and Roberts 1977). The south and east coasts, which receive the strongest wave energy for most of the year, are the exposed-windward margins (Fig. 1.7). The north coast, which receives strong to moderate wave energy, is the protected-windward margin. The leeward margin is the west coast of the island (Blanchon 1995; Blanchon and Jones 1995; Blanchon *et al.* 1997). Grand Cayman is sheltered from strong storm swell because it is centrally-located with respect to the other Caribbean Islands. Waves rarely exceed a height of 1.8 m and a period of 6 seconds (Rigby and Roberts 1976).

The waters around the island are remarkably clear, with a horizontal visibility of 40 - 60 m (Wells 1988). The clear water is due to the lack of river run-off from the island. Turbidity is typically low, but it depends on the direction and strength of the wind, the ocean roughness, and the availability of sediment.

Salinity of the water around the island is usually between 35 - 38‰. Semi-constricted bays and lagoons may experience fluctuating salinities as the amount and duration of rainfall fluctuates, and land run-off varies. Maximum fluctuations occur in North Sound, where the salinity periodically reaches 42‰ (Burton 1994).

1.7 MARINE GEOMORPHOLOGY

Well-defined, shallow reefs discontinuously fringe the north, south, and east coasts of Grand Cayman, and patch reefs are found along the west coast. All of the reefs around the island are rocky and rubbly in nature, with the substrate for reef growth being a linear ridge of storm rubble (Roberts 1994). Blanchon (1995) and Blanchon *et al.* (1997) found that hurricanes cyclically control reef anatomy. During hurricanes, live coral is ripped up and deposited as layers of rubble covering the entire

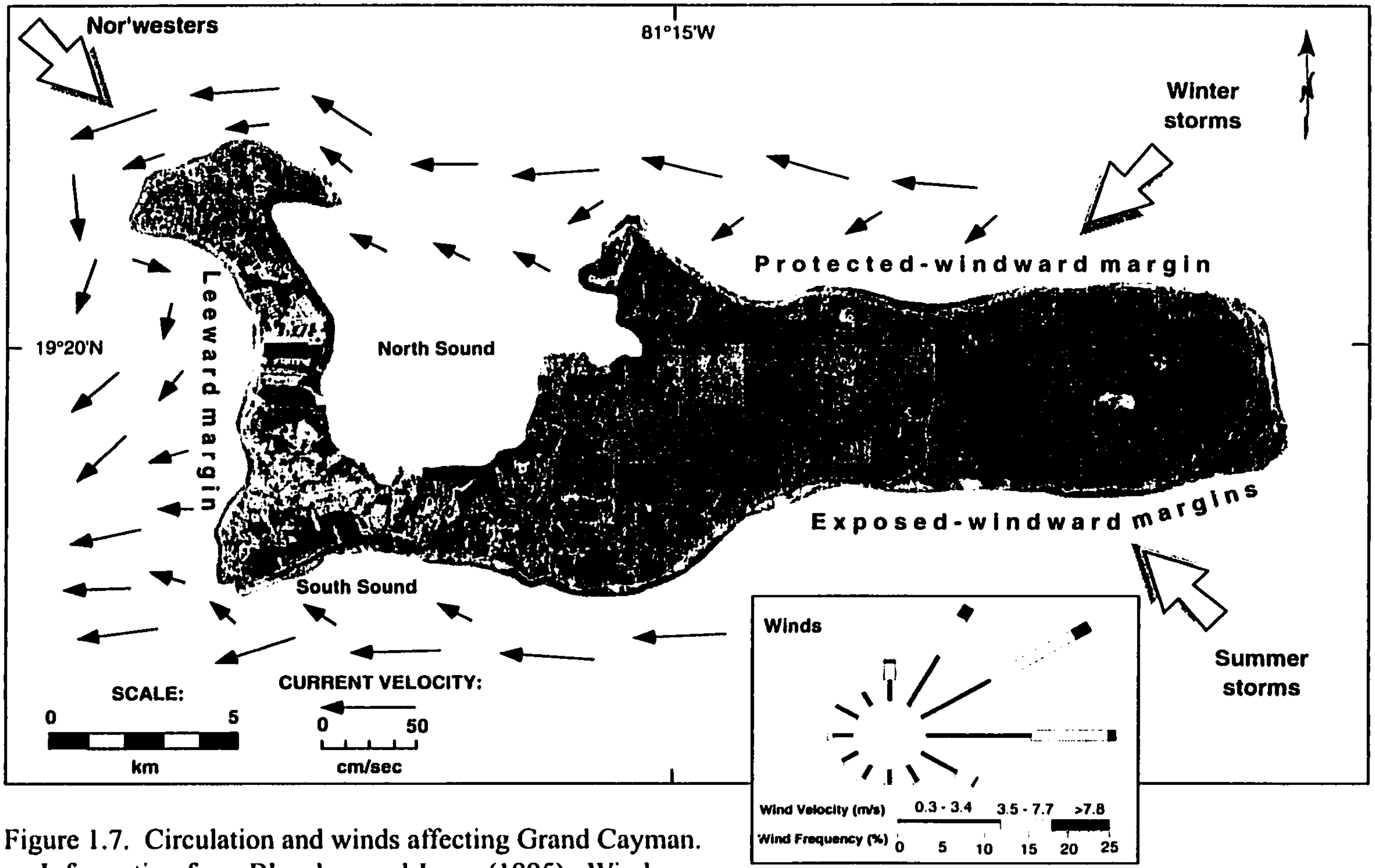

Figure 1.7. Circulation and winds affecting Grand Cayman. Information from Blanchon and Jones (1995). Wind rose (insert) modified from Darbyshire *et al.* (1976). Base map provided by the Department of Lands and Survey, Government of the Cayman Islands.

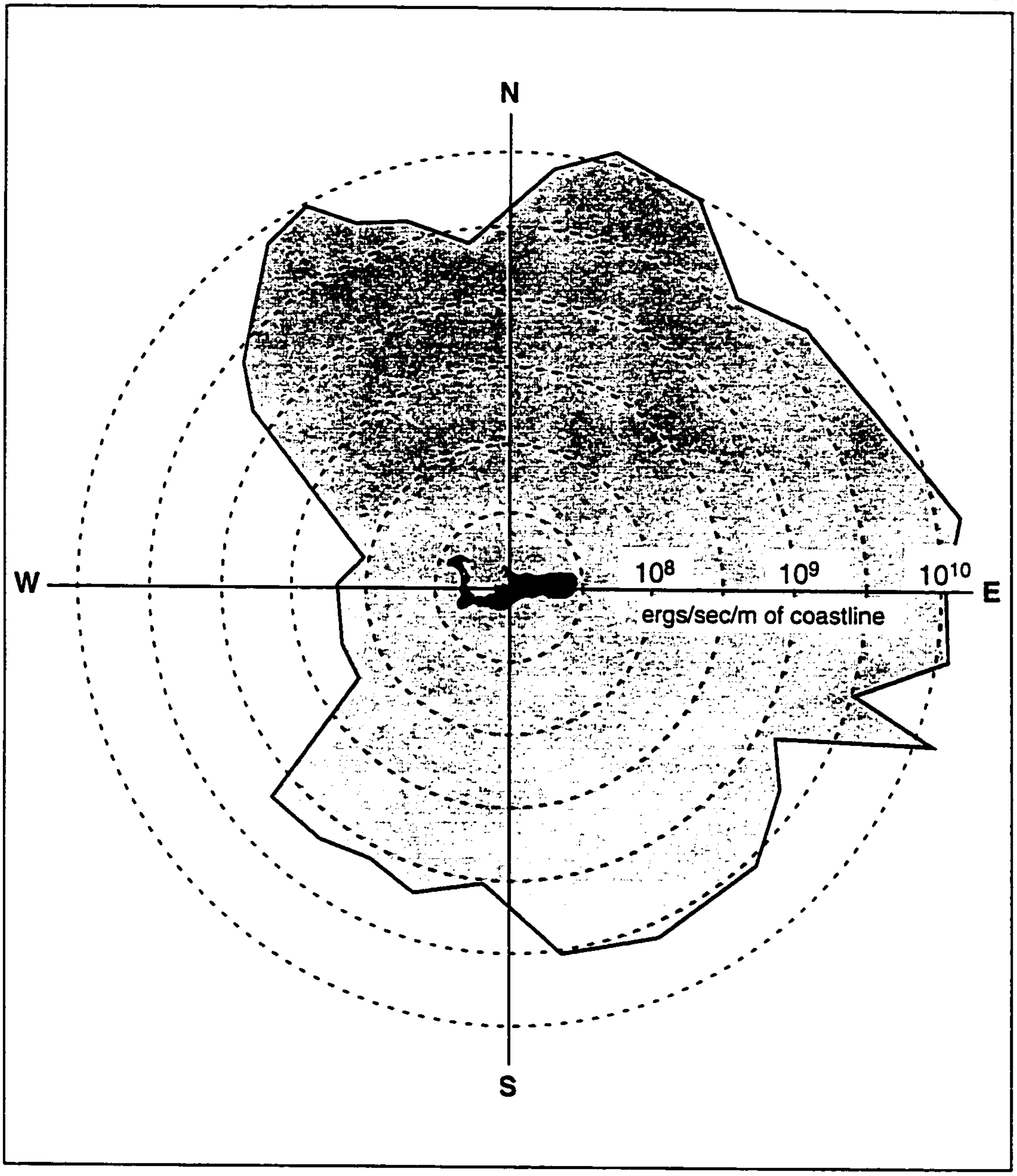

Figure 1.8. Annual mean wave power distribution on the coast of Grand Cayman in ergs/sec/m of coastline. Modified from Roberts *et al.* (1975).

reef. Between hurricanes, new coral and algal growth begins on the rubble mound. This destructive-regenerative process has formed the fringing reef complex on Grand Cayman. *Acropora palmata*, which is the dominant frame-building coral, is a significant source of the forereef and backreef lagoonal carbonate sediments. Several lagoons are developed on the north, south, and east coasts of the island, each having a distinctive geometry, topography, substrate, and benthic community. All lagoons are shallow, with an average water depth of less than 3 m and rarely exceeding 5 m (Roberts 1994).

The forereef shelf of Grand Cayman is typically less than 1 km wide, and predominant seaward-sloping terraces break the steep slope (Fig. 1.9). Emery (1981) described six terraces, whereas Woodroffe *et al.* (1983), Roberts (1974, 1983, 1994), and Blanchon and Jones (1995) described two terraces with water depths of 8 - 10 m and 12 - 40 m. The upper terrace is about 300 m wide and terminates landward at the shallow-water reefs. It is a limestone-floored terrace with profuse coral growth. It contains the stump and boulder zone and spur and groove zone, each defined by topography, biota, and substrate composition (Blanchon and Jones 1995). The lower terrace, which extends to the shelf edge, is 150 - 300 m wide. It is an area of thick sediment accumulation and active reef growth. The lower terrace encompasses

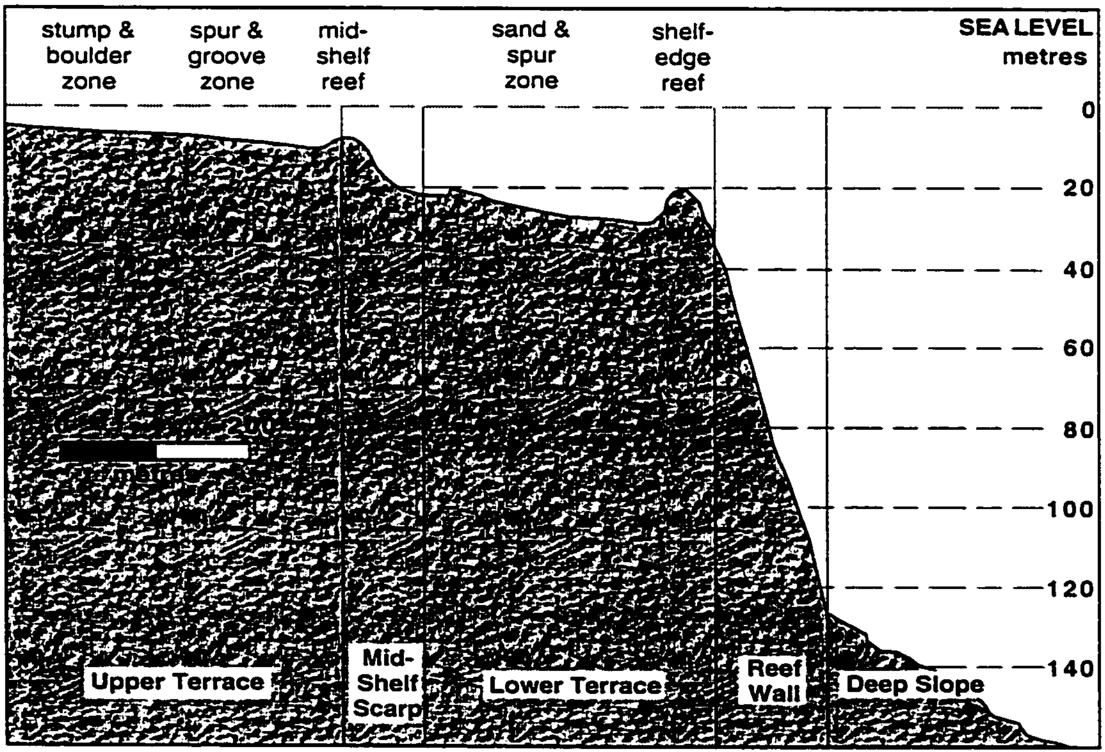

Figure 1.9. A schematic of the shelf profile perpendicular to the shore of the windward shelf of Grand Cayman. Based on information from Roberts (1994) and Blanchon and Jones (1995).

the spur and sand zone and the shelf-edge reef (Blanchon and Jones 1995). A steep mid-shelf scarp, 10 - 20 m below sea level, separates the upper terrace from the lower terrace (Fig. 1.9). It is almost completely obscured by thick, modern carbonate deposits. The upper and lower terraces were eroded during stand-stills in sea-level rise of the last deglaciation (Blanchon and Jones 1995). Seaward of the shelf edge, a near-vertical reef wall provides the transition to the deep slope, which begins at approximately 130 m water depth. The reef wall is composed of platy corals and sponges, with aphotic species emerging as water depth increases. Large limestone blocks, rubble, and fine, shallow water-derived carbonate sediments litter the floor of the deep slope (Roberts 1994).

1.8 PHYSICAL DESCRIPTION OF SOUTH SOUND

The study area is South Sound, a shallow lagoon on the southwestern coast of Grand Cayman (Fig. 1.2). Local Caymanians refer to it as a sound, because they consider it to be a passageway to the open sea. It is 5 km long, 1.1 km wide at the east end, and 275 m wide at the west end, encompassing an area of 3.4 km ^{2}. South Sound is fringed by land to the north and east, and by a reef to the south. Sand Cay, a small island, marks the western extremity of the lagoon. A red mangrove (*Rhizophora mangle*) swamp with an organic-rich, fine mud substrate is present along the northeastern edge. Most of the shore is lined with carbonate sand and sub-rounded coral rubble, 20 cm x 10 cm. South Sound is completely enclosed, except for the west end, where it is open to the Caribbean Sea. This narrow outlet was dredged in July 1971, to allow passage of small boats into and out of the lagoon (Wells 1988). The blunt point on the land adjacent to this passage is called Pull-and-be-damned Point (Fig. 1.10), a name which still reflects the difficulty of bringing non-motorized boats into the lagoon against the strong westward current. A band of beachrock parallels this point. A narrow, man-made channel cuts through the reef approximately half-way along its length (Fig. 1.10).

The varied substrate of South Sound supports a diverse biota that includes lobsters, mollusks, sea cucumbers, sea urchins, fan worms, and many types of fish, including jacks, parrotfish and stingrays. To protect the reef, flora, and fauna of South Sound, it was designated a Replenishment Zone in 1986 under the Marine Conservation Regulations (Wells 1988). The Replenishment Zone includes the area between the *Pallas* wreck in the west to Prospect Point in the east (Fig. 1.10). This designation prohibits the use of fish traps, spear guns, and most types of nets in the lagoon, and neither conch nor lobster may be removed.

To the east of South Sound is a small lagoon called John Bodden Bay. It was included in this study because of its similar conditions and proximity to South Sound. The two lagoons are separated by Prospect Point, a rocky point that juts out to the reef crest (Fig 1.10). John Bodden Bay is very narrow (< 250 m) so most of the lagoonal floor is covered in backreef rubble. It is 800 m long. Biota is slightly more sparse than that found in South Sound.

The average water depth in South Sound is 165 cm, with the maximum depth of 250 cm being in the centre of the lagoon (Fig. 1.11). From there, the water progressively shallows shoreward and towards the reef crest, giving the lagoon an elongated bowl-shaped geometry. In the east end of South Sound, the water depth increases to 50 cm within 100 m of the shoreline, but in the west end, the slope of the substrate is much steeper and the water reaches a depth of 50 cm within the first 50 m from shore. The water also shallows through the rubble zone to the reef crest, which is 10 - 50 cm below sea level. In the western-most part of the lagoon, the water deepens out beyond the end of the reef. More localized changes in bathymetry are attributed to blowouts, *Thalassia* banks, patch reefs, *Calianassa* mounds, and sediment-free areas.

John Bodden Bay is shallower than South Sound, with a maximum water depth of

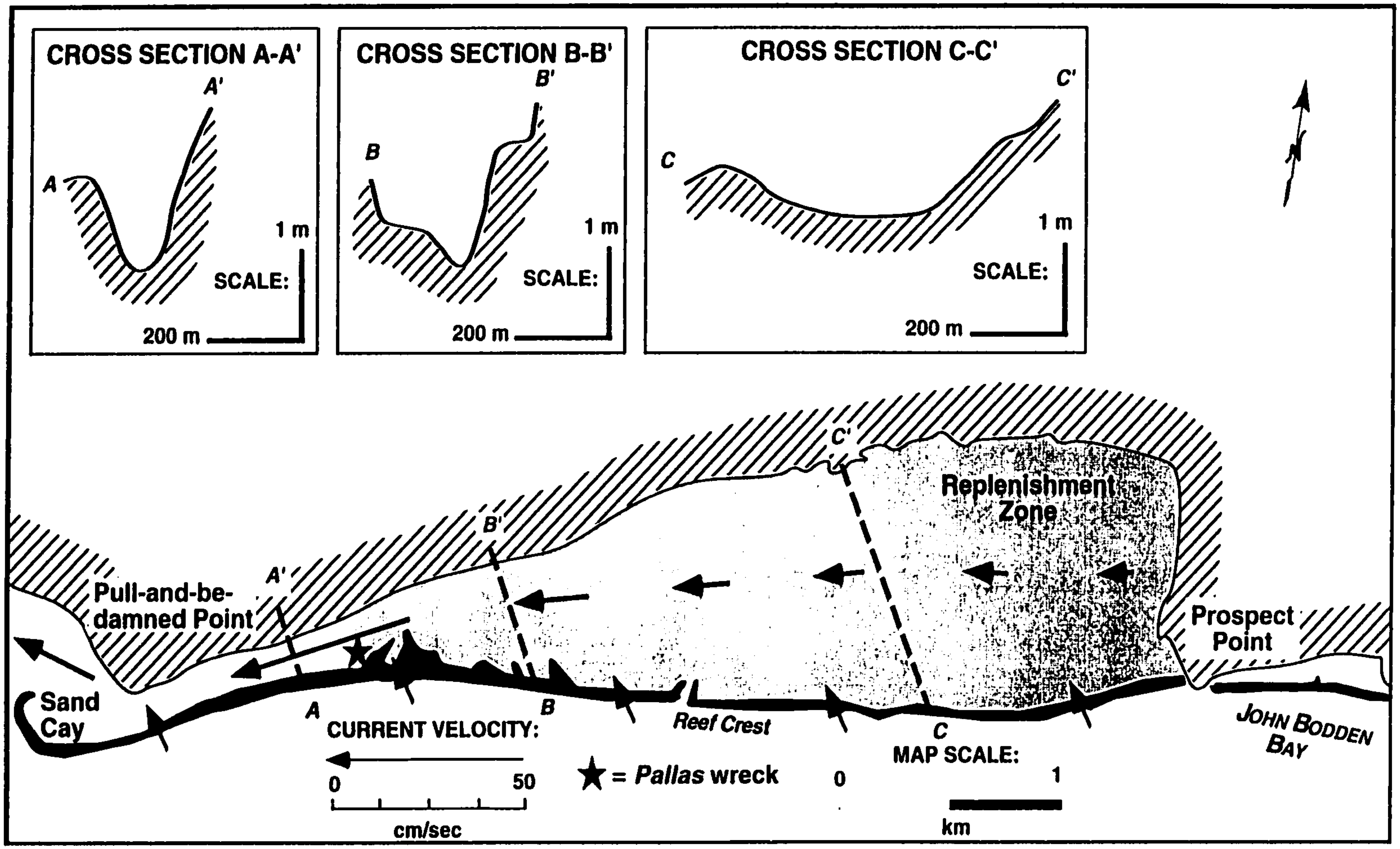

Figure 1.10. Direction and speed of currents in South Sound. Cross-sections illustrate the presence of a deeper moat just landward of the reefcrest. Modified from Roberts *et al.* (1975). Replenishment Zone area from Wells (1988).

100 cm (Fig. 1.11). The water also gradually shallows towards the shore and the reef crest. The substrate is composed almost entirely of rubble with very little sediment cover, so local bathymetric variations are minimal.

1.9 PREVIOUS WORK ON SOUTH SOUND

Roberts (1974) did much of the preliminary detailed work on the shelf and lagoons of Grand Cayman. He described the zonation of South Sound and the adjacent shelf. Rigby and Roberts (1976) described the offshore communities of the island. Roberts *et al.* (1975) measured tidal fluctuations, barometric pressure, and wind speed across the fringing reef bordering South Sound to determine the effect of reef morphology on incoming waves and current patterns.

Suhayda and Roberts (1977) produced a sediment isopach map of South Sound. They measured the wave-driven currents as they passed over the reef crest into the lagoon and found that waves breaking over the reef lost approximately 50% of their energy. Offshore waves break over the reef crest at 10 cm/sec and the lagoonal currents produced range from 2 cm/sec in the east to 45 cm/sec in the west, where the water is funneled west through the narrowest part of South Sound. This systematic variance in current strength is reflected in the sediments; in the east end the sediment is thick and fine-grained, whereas in the west the sediment is thin and coarse-grained. A moat is developed shoreward of the reef (Fig. 1.10) as a result of tidally-influenced wave-scouring as the waves break over the reef crest. This moat aids in the westward draining of the water in the lagoon. Besides the dominantly westward flow in South Sound, a seaward current is developed in the man-made channel cut through the reef, and a tidal current enhances the lagoonal currents near low-tide, when the waves break most intensely over the reef crest. Rigby and Roberts (1976) determined that the slight salinity variation in South Sound is primarily the result of organic-rich marsh waters draining into its northeastern corner. These reddish-brown, low-salinity

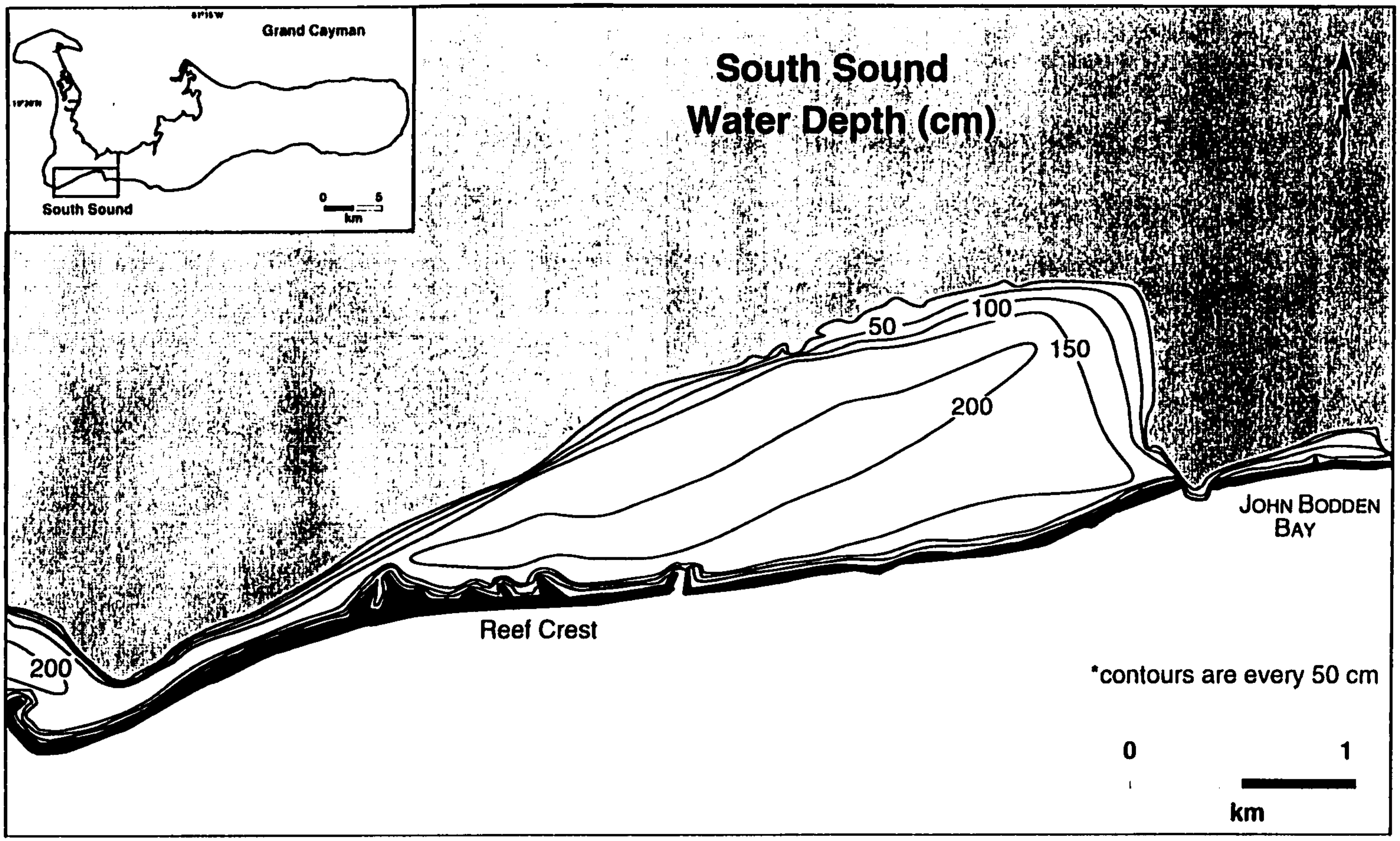

Figure 1.11. Water depth of South Sound.

waters are held close to the shore by the prevailing winds, and flow west to eventually merge with the clear, normal salinity ocean water.

Roberts (1983) noted that the southwestern shelf of Grand Cayman is a major site of sediment accumulation because of the strong westward current flowing through the lagoon (Fig. 1.10). Subsequently, Murray *et al.* (1977) concluded that sediments accumulate on the southwestern flank because this is where currents rapidly decelerate due to the dominant winds being northeasterly. The rapid and abundant sedimentation of this area restricts reef growth. Roberts and Sneider (1982) suggested that the sediment on the lower shelf is 5 - 10 m thick and the strong currents produced by tides in the narrow western side of South Sound is sufficient for sediment transport to the deep shelf.

Although Roberts (1974) focused on the physical processes operating in and around the Cayman lagoons, he did not provide details on lagoonal facies, flora, or fauna. Raymont *et al.* (1976) described the species composition of 35 reefs around the island. South Sound had healthy coral development behind the reef with large reef colonies of *Montastrea annularis*, *Acropora palmata*, and extensive fields of gorgonians (Raymont *et al.* 1976).

More recently, Tongpenyai (1989) and Tongpenyai and Jones (1991) used digital image analysis of South Sound and four other lagoons on the island to quantify the lagoonal substrates and biologic communities, and determine facies changes between 1971 and 1985. They found that *Thalassia* distribution in South Sound increased from 10% - 20% between 1971 and 1985 at the expense of sand. The foraminifera in South Sound were studied by Li (1997). He defined eight different foraminiferal assemblages and found that they correlated to substrate conditions, water quality, human activity, and natural forces acting in the lagoon. Kalbfleisch (1995) and Kalbfleisch and Jones (1998) defined the facies of Frank Sound and Pease Bay. By using image analysis to track sediment changes, they concluded that sediment deposition is primarily controlled by hurricanes.

1.10 OBJECTIVES OF STUDY

The study of the lagoon landward of the fringing reef of South Sound and John Bodden Bay focuses on carbonate sediment size, composition, and distribution. This will permit interpretations of carbonate sediment sources, transport directions, and general lagoonal processes. The examination of South Sound on such a small-scale has never been preformed before. Consistent, detailed descriptions and delineation of facies will be complimented by the most recent image analysis techniques. The main objectives for this thesis are:

1. to identify and describe the facies of South Sound;
2. to determine the spatial distribution of facies, and to see how these facies have changed over a period of 21 years;
3. to determine the sources of carbonate sediment in South Sound;
4. to assess the grain size distribution; and
5. to determine the sedimentary processes which act in this small, shallow, tropical lagoon, providing insights into the dynamics of the system.

CHAPTER 2

METHODS OF STUDY

2.1 FIELD METHODS

The field work involved detailed mapping and description of the substrate in South Sound and John Bodden Bay, and collection of sediment samples for analysis. Eight transects were sampled from the shore to the reef crest (Fig. 2.1). Accuracy was checked by comparing substrate features at known distances with those on 1:10,000 scale, 1992 aerial photographs. On each transect, water depth and sediment thickness measurements were taken at 25 m intervals, and a sediment sample was collected every 50 m. A graduated stainless steel rod was driven into the soft sediment until resistance was met, and the loose sediment thickness was recorded. Water depth was measured from the sediment surface to the mean wave height. Sediment samples were obtained from the lagoon floor during shallow dives. Each of the 74 samples were later carefully rinsed with fresh water and allowed to air dry. Detailed descriptions of the substrate, biota, flora and fauna composition, sedimentary textures, density, and diversity were taken continuously along each transect and any changes were noted. Opportunities to survey the lagoon floor between transects through reconnaissance swimming and boat work allowed facies boundaries to be constrained through ground-truthing. Underwater photographs of the different substrates were taken.

Sediment cores averaging 50 cm long were obtained where sediment thickness was sufficient, predominantly at the east end of the lagoon (Fig. 2.1). A 1.5 inch diameter PVC pipe was hammered into the sediment until it would not descend any further. A cap was fitted over the top end to create suction in the pipe. It was then slowly extracted from the sediment. The bottom end was immediately capped as it emerged. Once onshore, any excess water was drained out of the pipe and the top end was packed tightly to prevent sediment shifting during transport to Edmonton. A total of ten sediment cores were collected.

A 16-foot, 40 HP, flat-bottom boat was provided by the Department of Environment of Grand Cayman for work in areas of strong currents or where waves were high and choppy, such as near the reef crest. It was also used for support when SCUBA diving was required, such as for diversity counts and reef rubble measurement. For the diversity counts, a collapsable 1 m x 1 m grid was constructed with bolts and wing nuts fastening each of the four corners. Once positioned over the desired substrate with the boat or by swimming, the grid was randomly thrown and allowed to sink. The number of each type of plant or animal in the grid was systematically counted and recorded. If a plant was branching or had more than one blade, as is the case with *Thalassia*, the contained base of the plant was counted as one plant. Two to three grids were counted for each facies, for a total of thirteen grids (Fig. 2.1 and Appendix A).

Reef rubble measurement also required SCUBA diving. Once an area behind the reef crest was chosen, 50 randomly selected cobbles were measured with a ruler in the far backreef, midreef, and reef crest area. The length, width, and height of each cobble were recorded.

2.2 LABORATORY METHODS

Grain Size Analysis

Grain size analysis of 50 loose sediment surface samples and two sediment cores was performed according to the procedures described in Folk (1968). Most samples contained < 5% clay and silt, so wet sieving was not required. 100 g of each sample was sieved to prevent clogging of the screens with too much sand. It was weighed to 0.001 g and dry sieved on a W. S. Tyler Incorporated Ro-Tap Shaker, Model RX-29, using the W. S. Tyler Canadian Standard Sieve Series. Folk (1968), Friedman and

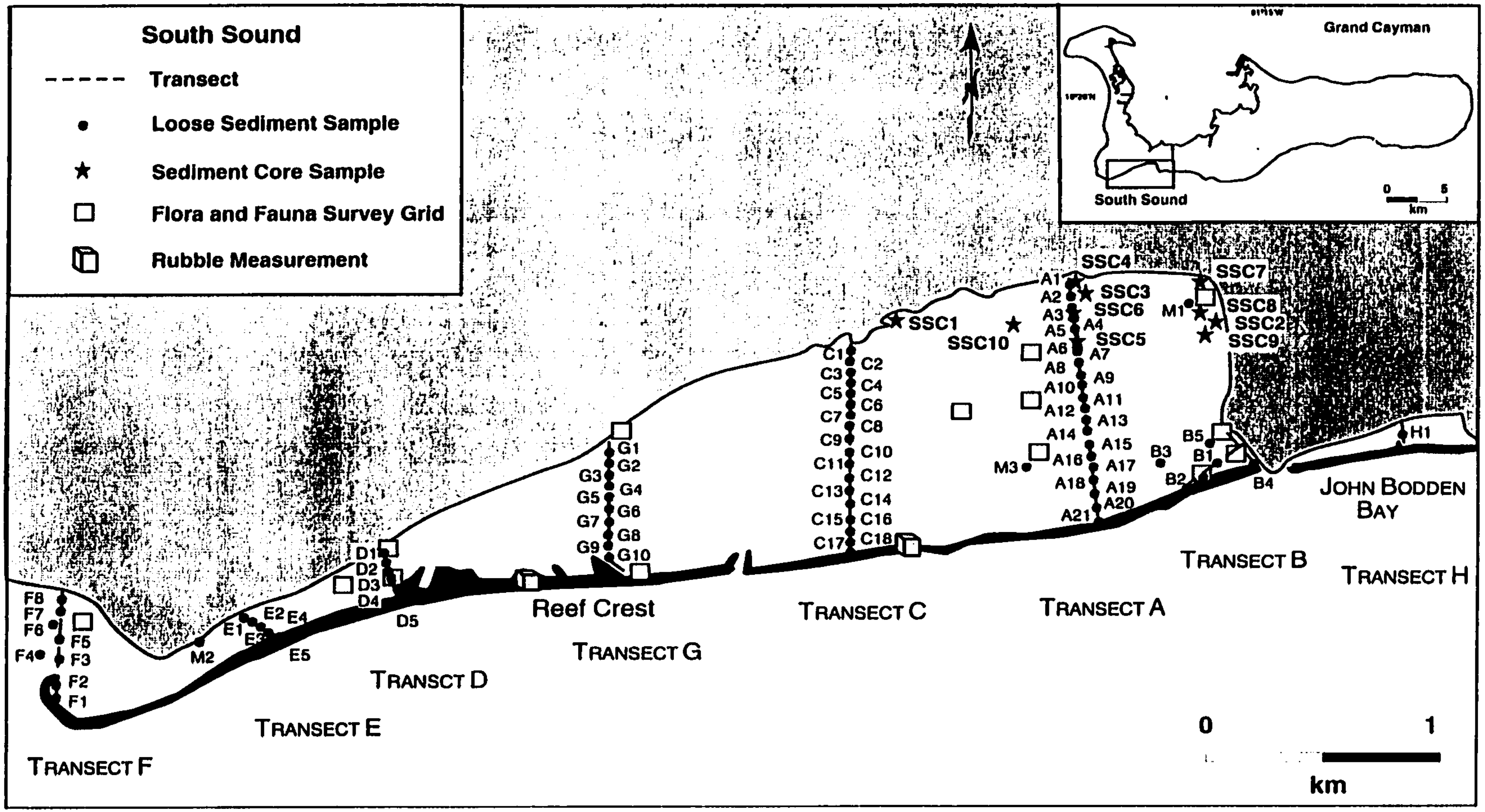

Figure 2.1. Map of South Sound showing the transect locations, the locations of loose sediment samples, cores, grid surveys, and rubble measurements. Sample numbers are shown along transects and core numbers are shown beside core symbol.

Jonhnson (1982), Lewis (1984), and Dalsgaard *et al.* (1991) suggested a sieving time of 10 - 20 minutes, and 15 minutes was found to produce good results for carbonate sediments. All samples along Transect A, as well as other select samples, were sieved using 1/4ø (Phi) sieve intervals and the remaining samples, which required only basic statistical parameters, were sieved using 1/2ø intervals. Each size fraction produced by sieving was weighed to 0.001 g.

Equations used for the calculation of statistical parameters follow those given by Folk (1966), Folk (1968), Folk and Ward (1957), and Boggs (1995) (Table 2.1). The mean, sorting, and skewness are determined from the plotted cumulative probability percentage graphs, but mode was determined from the highest peak on a histogram (Appendix B). Median was not calculated since it is not affected by the extremes of the curve, and therefore does not reflect the size of skewed sediments well (Folk 1968).

Table 2.1. Formulas for calculating grain size statistics by graphical methods. $ø_{15}$, $ø_{50}$, etc. refers to the phi value of the graph at the 15th, 50th, etc. percentile.

Graphic Mean	$M_Z = (ø_{16}+ø_{50}+ø_{84})/3$
Graphic Standard Deviation	$\sigma_i=(ø_{84}-ø_{16})/4+(ø_{95}-ø_{5})/6.6$
Graphic Skewness	$Sk_i = (ø_{84}+ø_{16}-2ø_{50})/2(ø_{84}-ø_{16})$ $+(ø_{95}+ø_{5}-2ø_{50})/2(ø_{95}-ø_{5})$

There are two potential errors in dry sieving which must be overcome to produce accurate results: 1) screen calibration; and 2) particle aggregation. Calibration of the screens is important for determining sensitive statistical parameters, such as skewness. Calibration was preformed on this particular set of screens by Kalbfleisch

(1995) and they have been used little since then. His conclusions were that no major or consistent errors were produced as a result of using this set of screens. Particle aggregation was not a major problem with these sediments because most of the aggregates were broken up from the sieving process alone. Nevertheless, each size fraction of the sieved material was examined using a binocular microscope, and the percentage of aggregates in 100 grains was determined. This percentage was then subtracted from the weight of the size class to which it belonged.

The larger sized cobbles from the rubble zone were measured directly with a ruler in the field and required different laboratory techniques. The mean diameter of each rubble piece was calculated by summing the length, width, and height in centimetres and dividing this number by three. The shape of each cobble was determined by plotting the ratio of the short axis/intermediate axis against the ratio of the intermediate axis/long axis, each being at 90° to each other (Fig. 2.2). This method of shape determination was introduced by Zingg (1935) and was later used by Hills (1998) to describe the shape of rhodoliths.

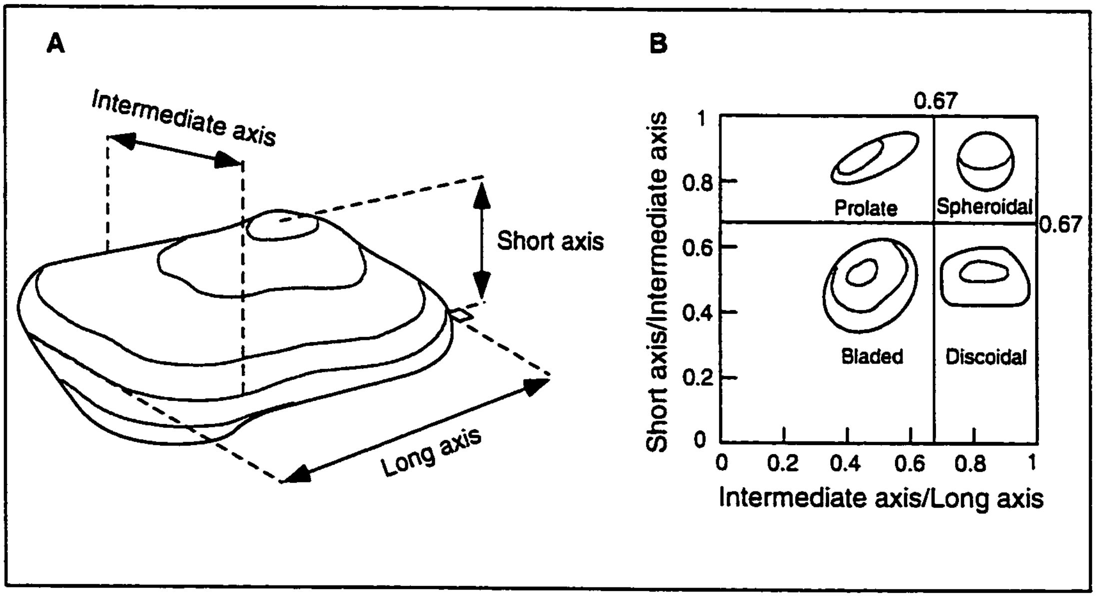

Figure 2.2. Determination of rubble form. **A)** Cobbles are measured along the long axis, intermediate axis, and short axis, each at 90° to each other. **B)** Zingg (1935) graph, used for the determination of shape.

Compositional Analysis

Thin sections were made from loose sediment samples, selected sediment samples from the cores, and sieved grain size fractions. The sediment was impregnated with blue epoxy in a vacuum and mounted on standard glass slides. At least 150 grains in each thin section were point-counted using a Jenapol polarizing microscope following the procedures described in Roberts (1976). Each count was started from the top right corner of the thin section, and controlled 2 mm traverses were made across the slide, to avoid counting the same grain twice. The grains were identified by comparison with illustrations and petrographic descriptions given by Ginsburg (1956), Roberts (1976), and Scholle (1978). The degree of boring and micritization was estimated for each grain (Table 2.2). The reproducibility of point counts using similar methods was reported by Ginsburg (1956) as ±5% and by Matthews (1966) as ±10%.

Thin sections were also studied to determine the composition of each grain size fraction after it had been sieved.

Table 2.2. Divisions for the degree of boring and micritization.

Degree of Boring and Micritization	
Low	< 25% of entire grain
Moderate	25% - 50% of entire grain
High	> 50% of entire grain

Core Logging

The PVC tube was cut in half lengthways using two 1/8 inch drill bits which were positioned on either side of it. It was split open using a thin wire and/or a utility knife. One half of the core was left undisturbed, whereas the other half was described in detail, and samples for grain size analysis, allochem identification, and thin sectioning were removed. Sediment size, composition, colour, and structure were recorded, as well as allochem abundance, density, and diversity. Based on these characteristics, subsurface facies were defined.

2.3 DIGITAL IMAGE ANALYSIS

The facies distribution of South Sound is determined in detail by using digital images to classify substrates of similar tone with each other. Two sets of vertical aerial photographs were used, selected on the basis of sufficient resolution, appropriate scale, clarity, and availability. A colour 1:10, 000 scale set, taken in 1992 was used for the recent facies distribution, and a 1971, black and white, 1:13, 000 scale set was used for establishing facies changes over time. Harris and Umback (1972) and Hopley (1978) found these scales to be appropriate for mapping coastal areas. Both sets of aerial photographs lack sun reflections, cloud cover, and whitecaps, allowing for an unobstructed view of the lagoon floor (Curran 1985). Change in scale over the aerial photograph due to changes in relief is not a problem because the area studied is relatively flat. Four photographs were required to cover the entire area of South Sound in the 1992 set, and the 1971 set contained three air photographs.

To create the digital images, each photograph was scanned into *Adobe Photoshop 5.0* using a *Hewlett Packard ScanJet 6100C* scanner, at 350 dpi x 350 dpi. Each file was saved as a digital image in Tagged Image File Format (TIFF). The software *Erdas Imagine v. 8.3.1* was used for most of the subsequent image analysis, on a *Pentium II x86*.

The facies were delineated separately on each of the seven air photographs by using the unsupervised classification technique. This highly computer-automated technique combines substrate areas of similar spectral characteristics into classes (Drury 1987; *Erdas* 1997). Each class then represents sections of the lagoon that have similar biotic and sedimentological characteristics. The resolution of the images was 2 ft x 2 ft (0.6 m x 0.6 m), so if a substrate patch in South Sound was larger than about 6 ft^2 (0.6 m^2), it could be individually recognized and classified. All unwanted information from the images such as land, shadows, white caps, and the open ocean beyond the reef crest were removed by placing them in a background class. All relevant classes, representing only the lagoon floor, were recoded, grouped into facies, and named (cf. Robinove 1977; Jensen 1986).

Each digital image was set to an arbitrary *xy* -coordinate system when it was imported into *Erdas Imagine v. 8. 3. 1*. Map coordinates were assigned to the image to correct for any distortions, skewing, warping, or rotation during photographing and processing, and to allow them to be spliced together accurately. This geocorrection process may slightly shift or change the pixels so, to ensure the accuracy of the classes, the classification was performed first on the original, unaltered data (Drury 1987). The air photographs were geocorrected using a 1994, high resolution, colour digital image of the entire island provided by the Department of Lands and Survey, Government of the Cayman Islands. At least thirty ground control points were selected for each image by choosing distinct features common to both the original image and the reference map. The ground control points need to be very accurate and widely dispersed across the image because all other points are extrapolated from these. The reference map was on the Universal Transverse Mercator (UTM) projection system in feet (UTM Zone 17 North), so each image was reset to these coordinates. This allowed the separate air photographs spanning South Sound to be combined together to create complete maps of the lagoon floor, and complete facies maps.

The facies structure in South Sound was spatially and temporally quantified using statistical calculations. The thematic classified 1971 and 1992 maps of South Sound were reformatted in *Arc\Info v. 7.0* and statistical calculations were performed using *Fragstats*Arc v. 2.0.* Equations are taken from McGarigal and Marks (1994).

Number of patches per class (NP) is a simple and unitless, but important, statistic:

$$NP = n_i$$

where n_i represents the total number of patches per class.

Patch density (PD) is fundamental for describing the structure of a region. It is similar to number of patches (NP) but it expresses the number of patches on a unit per area basis:

$$PD = \frac{n_i}{A}(10{,}000)(100)$$

where A is the area in m^2. The result is the number of patches per 100 hectares (ha).

Also based on the number of patches is mean patch size (MPS). MPS (in hectares) is defined as:

$$MPS = \sum_{j=1}^{n} \frac{a_{ij}}{n_i}\left[1/10{,}000\right]$$

MPS equals the sum of the areas (m^2) of all patches for a class (a_{ij} from n to $j = 1$), divided by the number of patches of the same type, divided by 10,000 (to convert to hectares).

Patch size standard deviation (PSSD) measures absolute variation (in hectares) and is a function of mean patch size and the difference in patch size among patches.

Patch size coefficient of variation (PSCV) measures the relative variability about the mean rather than the absolute variability, so it is often a more reliable indicator of patch variability. The mean patch size does not have to be considered for interpretation because PSCV is given as a percentage. PSSD and PSCV are calculated as:

$$\mathrm{PSSD} = \sqrt{\sum_{j=1}^{n} \frac{\left[a_{ij} - \left(\frac{\sum_{j=1}^{n} a_{ij}}{n_i}\right)\right]^2}{n_i}}$$

$$\mathrm{PSCV} = \frac{\mathrm{PSSD}}{\mathrm{MPS}}(100)$$

CHAPTER 3

DISTRIBUTION AND DESCRIPTION OF FACIES IN SOUTH SOUND

3.1 INTRODUCTION

The facies of South Sound were defined by merging data collected during field work, laboratory work, and digital image analysis. Digital image analysis of aerial photographs allows accurate placement of facies boundaries, and enables a more accurate division of facies than can be achieved through field mapping alone. The field and laboratory work provide the detailed information and ground truth. Each of the facies in South Sound can be recognized by its biota, sedimentary components, grain size, and position. The facies found in South Sound are the: 1) *Thalassia* Facies, 2) Sand Facies, 3) Rock Bottom Facies, 4) Rubble Facies, 5) Coral Head Facies, and 6) Brown Algae Facies. The *Thalassia* Facies and Sand Facies can be further divided, based primarily on the image analysis tonal classification.

3.2 *THALASSIA* FACIES

The *Thalassia* Facies is characterized by variable density and diversity. It is predominantly found along the shore from 5 m to as far as 380 m into the lagoon (Fig. 3.1). Isolated *Thalassia* banks to very large *Thalassia* patches are found adjacent to the Rubble Facies, within 60 m of the reef crest (Fig. 3.1). The *Thalassia* Facies can be divided into the Very Dense, Dense, Medium, and Sparse *Thalassia* Facies according to the number of plants per square metre, tone on the air photograph, biotic composition, and position in South Sound (Table 3.1). The Very Dense *Thalassia* Facies (> 2000 plants/m^2) and the Dense *Thalassia* Facies (500 - 2000 plants/m^2) have blades that are long and wide. The blades in the Medium *Thalassia*

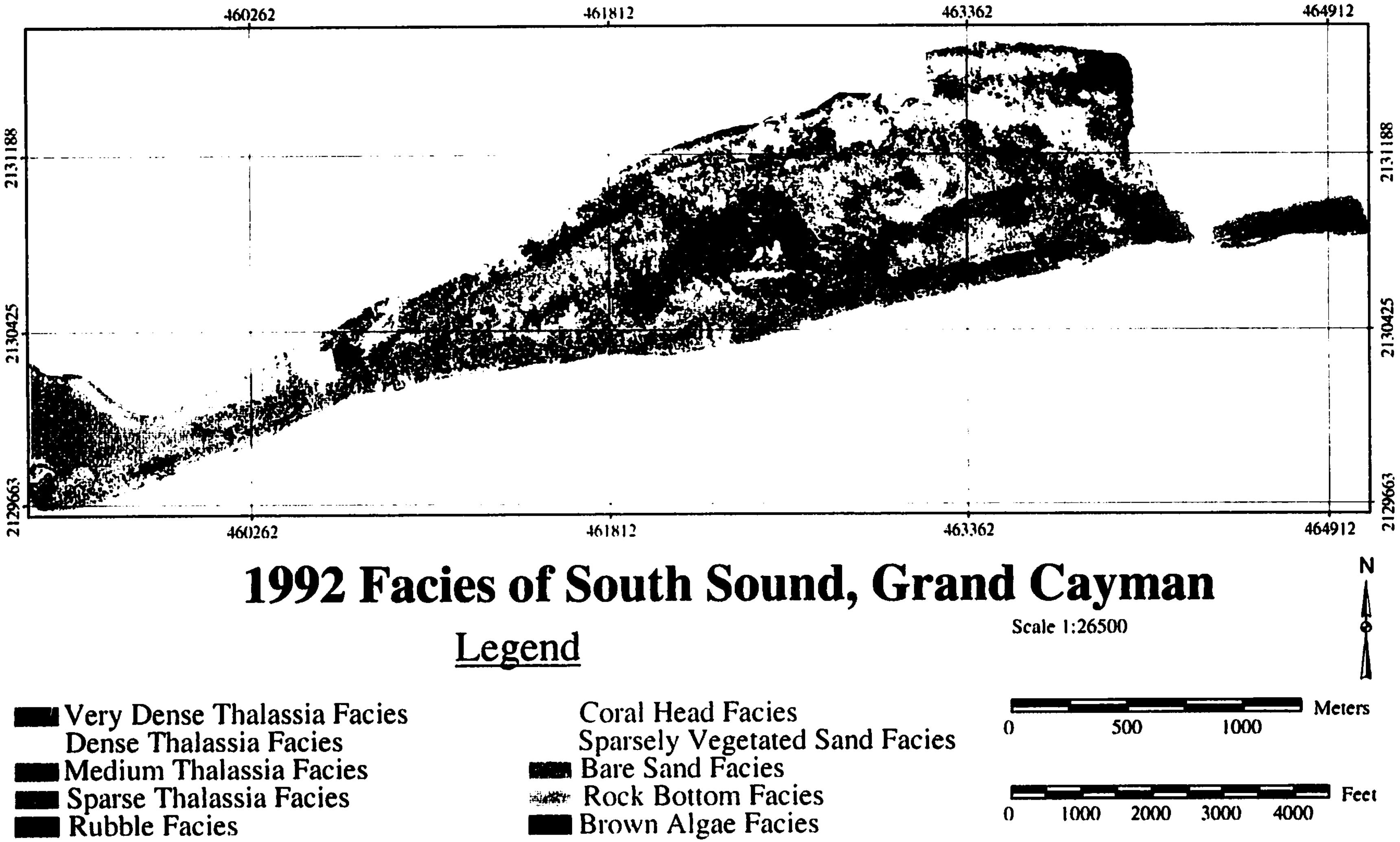

Figure 3.1. Classified 1992 facies map of South Sound.

Table 3.1. Comparison of Very Dense, Dense, Medium, and Sparse *Thalassia* Facies. VC = Very Common, C = Common, R = Rare, and VR = Very Rare.

Facies	Plants/m^2	Tone on Aerial Photographs	Associated Biota	Position in South Sound	Grain Size Ø			Dominant Sediment Components
					Min	Mean	Max	
Very Dense Thalassia	> 2000	Darkest	Thalassia testudinum (VC) Tedania (C) Siderastrea Siderea (C) Halimeda sp. (C)	Discontinuous thin band along shore, eastern South Sound	N/A	2.3 fine sand	N/A	Mollusks 41% Halimeda 21% Foraminifera 17%
Dense Thalassia	500 - 2000	Dark	Thalassia testudinum (VC) Halimeda sp.(R) Tedania (C) Porites porites (R) Siderastrea radians (R) Siderastrea siderea (R) Favia fragrum (R)	Parallels shorline along length of lagoon	1.9	1.2 medium sand	1.0	Mollusks 52% Halimeda 29% Foraminifera 9%
Medium Thalassia	250 - 500	Medium	Thalassia testudinum (VC) Syringodium filiforme (R) Halimeda sp. (C) Penicillus dumentosis (C) Caulerpa cupresoides (VR) Avrainvillea asarifolia (R) Dasycladus vericularia (VR) Udotea flabellum (VR) Acetabularia calyculus (R) Dictosphaeria cavernosa (VR) Dictyota sp. (VR) Turbinaria tricostata (VR) Tedania (C) Porites porites (C) Siderastrea radians (C) Favia fragrum (R)	Scattered patches throughout the lagoon, from shore to reef crest	2.4	1.5 medium sand	0.5	Mollusks 54% Halimeda 26% Foraminifera 9%
Sparse Thalassia	< 250	Medium-Light	Thalassia testudinum (VC) Syringodium filiforme (C) Halimeda sp. (C) Penicillus dumentosis (C) Caulerpa cupresoides (VR) Avrainvillea asarifolia (R) Dasycladus vericularia (VR) Udotea flabellum (R) Acetabularia calyculus (R) Dictosphaeria cavernosa (VR) Dictyota sp. (R) Turbinaria tricostata (VR) Tedania (C) Porites porites (C) Siderastrea radians (R) Siderastrea astreoides (C) Favia fragrum (R)	Fringes Sparsely Vegetated Sand Facies on landward side	1.9	1.2 medium sand	0.6	Mollusks 67% Halimeda 10% Foraminifera 9%

Facies (250 - 500 plants/m^2) and the Sparse *Thalassia* Facies (< 250 plants/m^2) tend to be shorter and thinner. A mottled texture is apparent on the aerial photographs because the density and length of plants varies from one area to the next, even within a facies (Fig. 3.2). The Medium *Thalassia* Facies is the most widespread *Thalassia* Facies in South Sound. Water currents are low in the Very Dense and Dense *Thalassia*, and currents are low to moderate farther out from shore in the Medium and Sparse *Thalassia*.

Thalassia testudinum, commonly known as turtle grass, is an angiosperm that has an extensive support system of roots and well-anchored rhizomes. The branching root system extends below the sediment surface to depths of up to 60 cm. It grows in soft, sand-sized sediment that is no less than 5 cm thick, and in water from 5 - 240 cm deep. This sea grass reproduces both by rhizome root growth and by seed dispersal, but reproduction is slow (Scoffin 1970). There are usually three to four blades per plant, and each blade is green, flat and erect with rounded tips. A single blade in South Sound averages 35 - 47 cm long and 8 - 12 mm wide. If individual blades have not been previously broken by bioerosion or storms, they will be shed after about two months of active growth (Hanlon and Voss 1975). Although *Thalassia* can tolerate temperatures from 20 - 36°C, the optimum temperature range is 28 - 30°C (Zieman 1975). Salinity tolerances are between 25 - 40‰ (Moore 1963), but McRoy and McMillan (1977) found that *Thalassia* could survive in salinities of up to 60‰.

There is very little leaf detritus trapped in the *Thalassia* Facies in South Sound, but single, broken blades floating on the surface of the water are common. The thickest accumulation of ripped-up blade detritus was found at the beginning of Transect D, where much of it has been washed up onshore. This accumulation is approximately 1.5 m thick, 3 m wide, and 8 m long.

Thalassia blades slow currents and allow fine sediment to settle out of

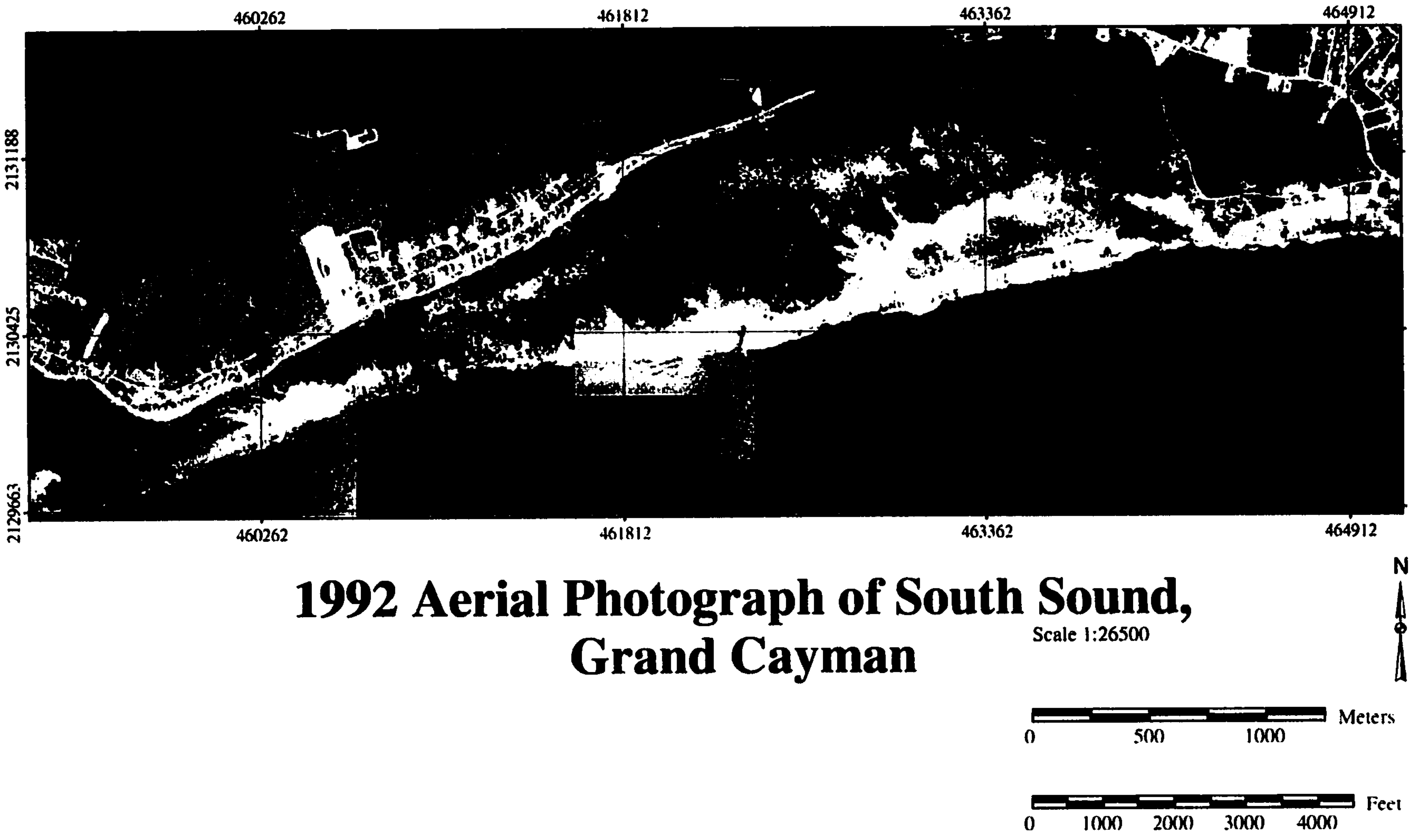

Figure 3.2. Aerial photograph of the substrate of South Sound in 1992.

suspension. Almasi *et al.* (1987) found that there was a mean current speed reduction of 18.5% in sea grass beds. The rhizomes of *Thalassia* stabilize the substrate and bind it together, so small patches of Medium to Dense *Thalassia* tend to be on built-up banks with the surrounding sediment being at a lower level. In South Sound, these banks range from 5 - 10 m long, and 10 - 40 cm high.

Despite the strong erosion prevention potential of *Thalassia*, blowouts may form (Fig. 3.3A). Blowouts are crescent-shaped erosional depressions initially formed during storms (Neumann *et al.* 1970). These depressions continue to increase in size where waves and currents are moderate to high. Erosion in dense *Thalassia* starts at currents of 150 cm/sec, but this depends on eddies produced and the roughness of the sediment surface (Scoffin 1970). The seaward edge of the blowouts is steep and convex, where the rhizomes of the *Thalassia* are exposed. Blowouts in South Sound are commonly 5 - 10 m in diameter and 20 - 50 cm deep. They are found in *Thalassia* adjacent to the sand facies in the east end of the lagoon, and in the western outlet.

Sedimentology

The surface sediment of the *Thalassia* Facies is a poorly sorted, near-symmetrical, medium skeletal sand (Table 3.1). Mean grain size decreases from a medium sand to a fine sand in the shoreward direction as *Thalassia* becomes progressively more dense (Fig. 3.4). An exception to this trend is found in the Medium *Thalassia* Facies, which is slightly finer-grained than the Sparse and Dense *Thalassia* Facies. Sorting becomes poorer as *Thalassia* density increases. Skewness is minimal but varies slightly with clay content.

Silt and clay content in South Sound rarely exceeds 5% dry weight. Besides the Brown Algae Facies, the Very Dense *Thalassia* Facies has the largest percentage of silt and clay in the lagoon (13.3%). It is the most negatively skewed of the *Thalassia*

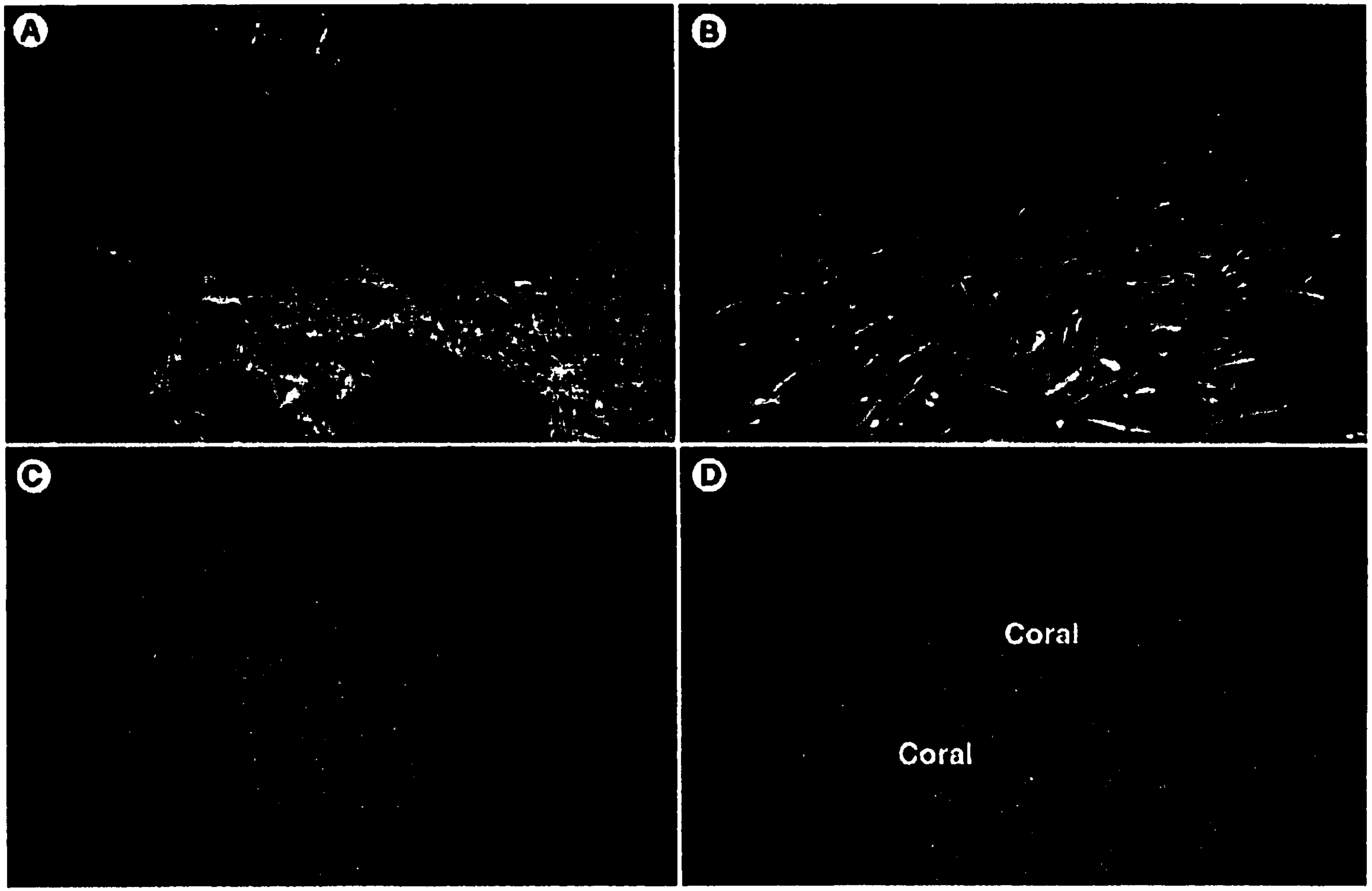

Fig. 3.3. **A)** *Thalassia* blowout in John Bodden Bay. Height of blowout edge is about 30 cm. **B)** The Dense *Thalassia* Facies. Individual blades are about 25 cm long. **C)** Sea cucumber (about 30 cm long) in the Sparse *Thalassia* Facies. **D)** Corals (14 - 20 cm diameter) in the Sparsely Vegetated Sand Facies.

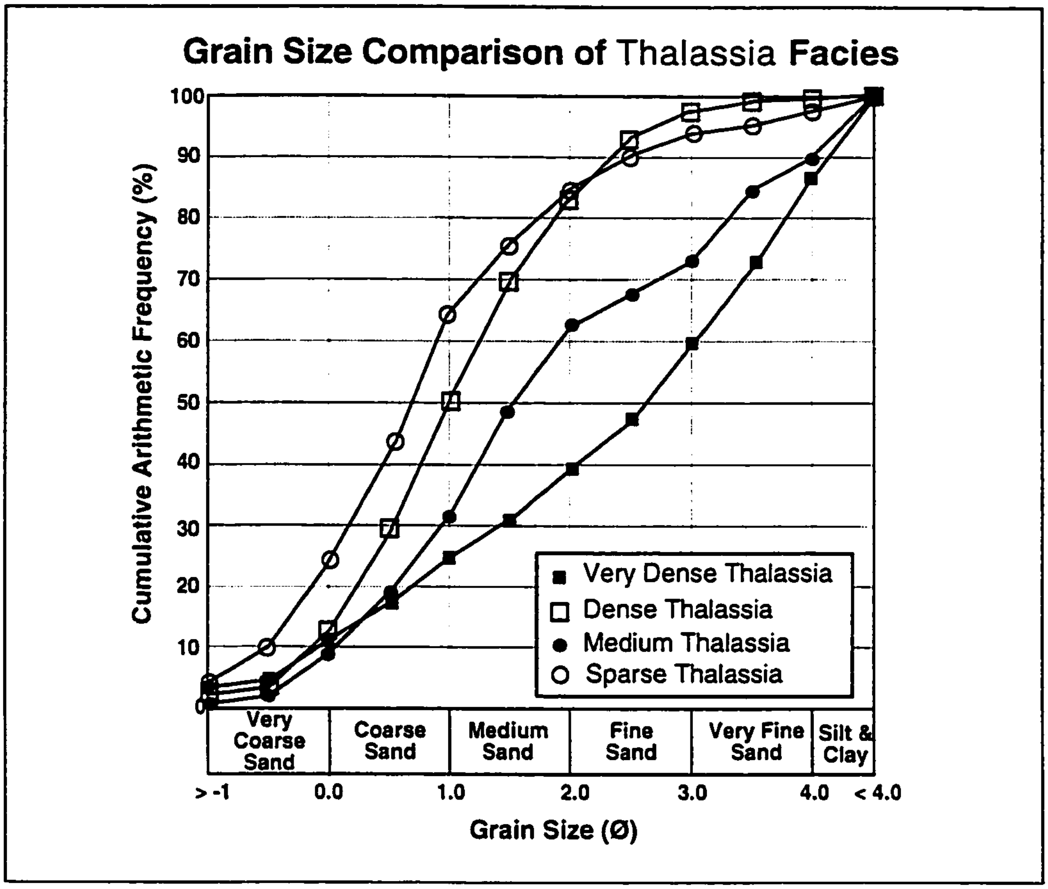

Figure 3.4. Graphical comparison of the grain size of Very Dense, Dense, Medium, and Sparse *Thalassia* Facies.

Facies because it contains the most clay.

Sediment in the *Thalassia* Facies is composed of mollusks (52%), *Halimeda* plates (23%), benthic and planktonic foraminifera (8%), red algae (6%), and coral fragments (1%) (Fig. 3.5). Almost all grains have some degree of boring and micritization, but the facies has moderate micritization and low boring overall (Table 3.2). The most extensively micritized grains were consistently bivalves and red algae, and bivalves had the most borings. Foraminifera were the least affected. A thin section survey of grain size fractions indicates that the size distribution generally is not affected by grain composition. In the *Thalassia* Facies, the only trend observed

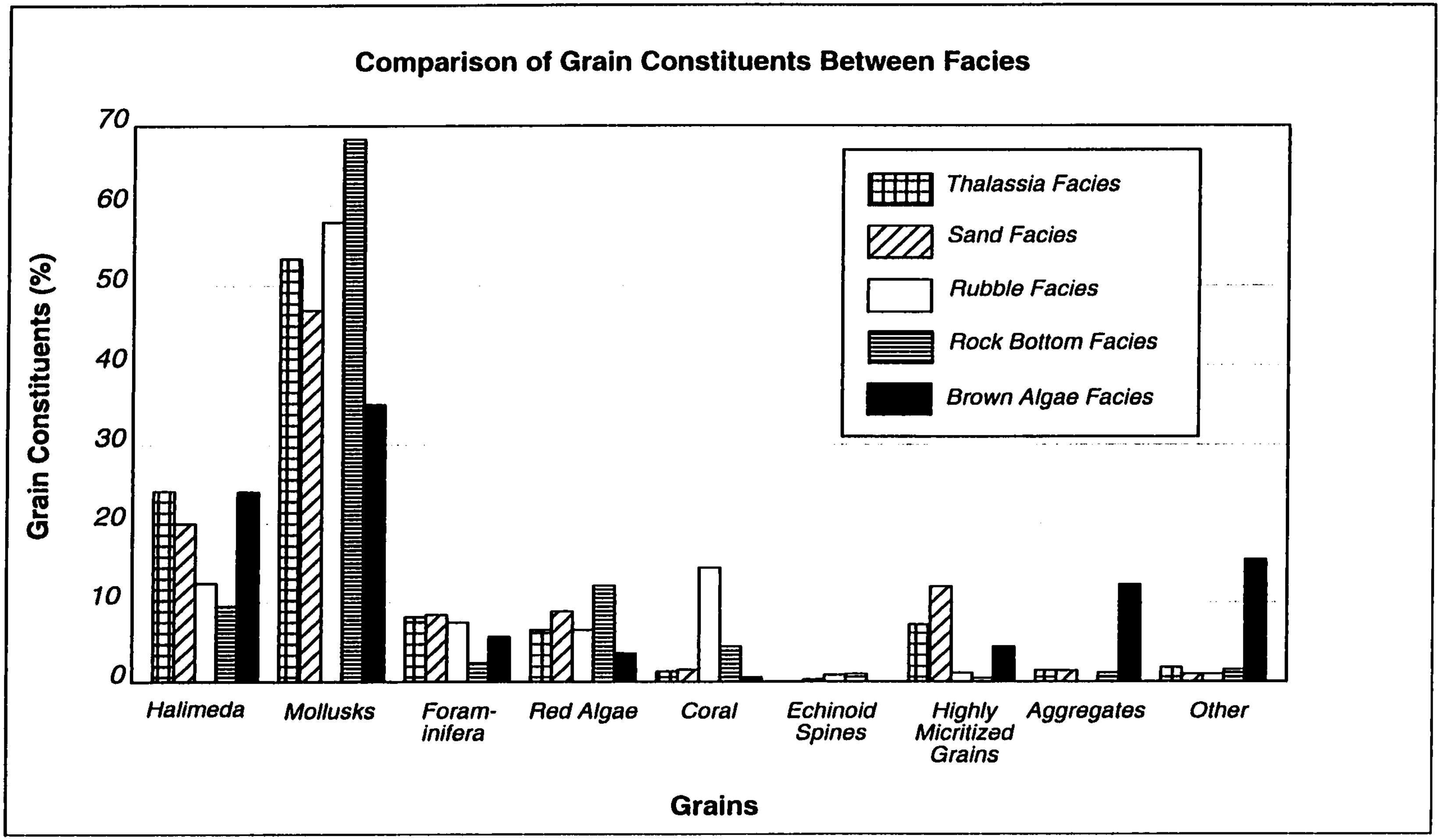

Figure 3.5. Graphical comparison of the grain constituents between the facies.

is that unfragmented benthic foraminifera are concentrated in the 0.0ø to 2.5ø size range, and whole planktonic foraminifera are concentrated in the 2.5ø to 3.5ø size range.

Biological Communities

The Very Dense and Dense *Thalassia* Facies are dominated by the sea grass *Thalassia testudinum*, which represents 85 - 99% of the vegetation (Fig. 3.3B; Appendix A). Algae, sponges, and other biota are rare (Table 3.1). The Medium and Sparse *Thalassia* Facies have various amounts of green, brown, and red algae, with the green algae being the most abundant. Although the angiosperm *Syringodium filiforme* (manitee grass) grows with the *Thalassia* at some locations, it is generally sparse.

The corals *Porites porites*, *Siderastrea radians*, and *Favia fragrum* are found in the Dense to Sparse *Thalassia* Facies (Table 3.1). These coral species can tolerate the temperature and salinity changes and the high sedimentation conditions. Individual corals in the *Thalassia* Facies, which do not grow to a large size, are commonly < 30 cm in diameter. The orange tube sponge, *Tedania*, is abundant, growing in even the Densest *Thalassia* Facies. Brown chimney and bright orange massive sponges are also present.

The seagrass community supports a wide variety of fauna by providing shelter, substrate, and/or food. Sea cucumbers (*Holothuria mexicans*) are abundant in the Medium to Sparse *Thalassia* Facies with a sandy substrate (Fig. 3.3C), whereas the short-spined sea urchin, *Tripneustes ventricosus*, is less common. Thousands of microscopic, stinging hydroids live among dense *Thalassia* blades, especially in the east end of the lagoon. Vertebrates such as the green sea turtle (*Chelonia mydas*) and parrotfish (*Sparisoma radians*) are common, since they graze on sea grasses. The

Table 3.2. Comparison of sedimentology between the five facies found in South Sound.

Facies	Average Clay Content	Grain Size Ø			Sorting Ø	Skewness	Degree of Micritization	Degree of Boring
		Min	Mean	Max				
Thalassia	*3.2%*	*2.4*	*1.4*	*0.5*	*1.14*	*0.03*	*Moderate*	*Low*
Sand	*1.3%*	*2.2*	*1.8*	*1.4*	*1.02*	*-0.09*	*Moderate*	*Low*
Rubble								
sediment	*0.3%*	*1.5*	*0.6*	*-0.3*	*0.92*	*-0.07*	*Low*	*Moderate*
clasts	*0.0%*	*-6.0*	*-6.8*	*-7.3*	*0.73*	*-0.05*		
Rock Bottom	*0.2%*	*0.8*	*0.4*	*0.0*	*0.96*	*-0.02*	*Low*	*Moderate*
Brown Algae	*14.3%*	*3.0*	*2.0*	*0.9*	*1.46*	*0.03*	*Moderate*	*Low*

surface conical sand mounds produced by burrowing shrimp are very common in South Sound, especially in the *Thalassia* Facies and the Sand Facies. These *Callianassa* mounds average 30 cm in diameter and 10 - 20 cm high. The shrimp expels sand from the centre of the mound as it burrows deeper. The *Callianassa* mounds range from being densely packed to widely scattered across a given area.

Mollusks commonly reside between the *Thalassia* plants and on the blades. The most noticeable gastropods are the conch, *Strombus gigas* and *S. costatus*. Other gastropods include *Smaragdia viridis*, a small green gastropod that lives on grass blades, *Cerithium litteratum, Tegula fasciata,* and various bubble shell gastropods. Common bivalves include *Protothaca granulata*, which prefers a muddy substrate, and *Chione cancellata*. Keyhole limpets are also found in the *Thalassia* Facies.

Each *Thalassia* blade supports a multitude of epibionts that include encrusting red algae, other coralline algae, foraminifera, and serpulid worms, as well as fine sediment (cf. Ivany *et al.* 1990). The blades grow up from the base of the plant, so the longest and oldest blades have the thickest and most abundant epibiont coverings. When the grass blades fall, this heavy encrustation disintegrates to produce a fine calcite mud (Stockman *et al.* 1967).

3.3 SAND FACIES

The Sand Facies ranges from a sand substrate with very sparse vegetation (Sparsely Vegetated Sand Facies) to a completely bare, medium-grained carbonate sand (Bare Sand Facies). The Sand Facies is located in the central part of South Sound, landward of the Rubble Facies and fringed shoreward by the Sparse *Thalassia* Facies (Fig. 3.1). It is found in water 170 - 240 cm deep (Fig. 1.11), where the westward flowing currents are moderate in strength. The Sparsely Vegetated Sand Facies rims the Bare Sand Facies. The high reflectivity of the Sparsely Vegetated

Sand Facies on the aerial photographs is muted by a thin vegetation cover. The Bare Sand Facies appears white on aerial photographs (Fig 3.2), and is found in various patches that are scattered throughout the lagoon. Lunar ripple crests in the sand have an orientation parallel to the reef crest.

Sedimentology

The sediment of the Sand Facies is a poorly sorted medium sand with an average grain size of 1.8ø. The poor sorting can be recognized from the large size range between the minimum and maximum grain size (Table 3.2). Skewness is slightly negative. The Sparsely Vegetated Sand Facies, which is only slightly finer-grained and better sorted than the Bare Sand Facies, has a mean grain size of 1.9ø. Skewness is the same in both Sand Facies. There is almost no silt- and clay-sized sediment (1.3%). Overall, the sediment in the Sand Facies is slightly finer than that of the *Thalassia* Facies (Table 3.2).

The composition of the sediment grains in the Sand Facies is similar to that of the *Thalassia* Facies, except that there are more red alga. The most abundant biotic sediment components are mollusks (47%), *Halimeda* (20%), benthic and planktonic foraminifera (9%), red algae (9%), and coral fragments (1%). Very few of the grains are aggregated (Fig. 3.5). There are slightly less completely micritized grains than in the *Thalassia* Facies, and usually < 25% of each grain has been bored. Composition does not affect grain size distribution in the Sand Facies, except that whole *Halimeda* plates are concentrated between -1.0ø and 1.5ø.

Biological Communities

The Sparsely Vegetated Sand Facies is characterized by scattered *Thalassia* and *Syringodium filiforme*. The algal population is dominated by *Halimeda* sp., *Penicillus*, and the brown algae *Dictyota*. Less abundant are *Stypopodium* sp., and *Caulerpa cupressoides*. The Bare Sand Facies has almost no vegetation.

Corals in the Sparsely Vegetated Sand Facies are rare but *Acropora cervicornis* and *Siderastrea siderea* are found locally (Fig. 3.3D). Ripped up sea fans (*Gorgonia*) are present in some areas.

Fauna living in the Sand Facies include sea cucumbers (*Holothuria mexicans*) and burrowing stingrays (*Dasyatis americana*). The stingrays leave behind depressions in the sand that are about 20 - 30 cm deep and 1 - 1.5 m in diameter. Large schools of jackfish frequent the area. Other fauna include starfish (*Oreaster* sp.) and echinoids (*Clypeaster rosaceus*). Mollusks include *Strombus gigas*, *Cerithium litteratum*, *Tegula fasciata*, *Tellina radiata*, *Protothaca granulata*, and various keyhole limpets.

3.4 ROCK BOTTOM FACIES

The hard substrate of the Rock Bottom Facies is located in the outlet at the western end where the currents are strongest in South Sound; and just to the west of Prospect Point where strong waves wash over the reef crest. Much of John Bodden Bay is characterized by a hard rocky bottom (Fig. 3.1). Sediment in the Rock Bottom Facies is generally 1 - 3 cm thick and confined to depressions in the rock surface. Poorly sorted lithoclasts, 0.5 - 50 cm in length are abundant. This facies has the highest reflectivity and appears bright white on the aerial photographs (Fig 3.2).

Sedimentology

The Rock Bottom Facies is composed of a near-symmetrical, moderately sorted coarse sand. The clay content is the lowest of all the facies in South Sound, at 0.2% (Table 3.2). The biotic composition of the sediment is unique, because of the high percentage of red algae (12%) and the low percentage of *Halimeda* (9%). Other components are mollusks (68%), coral (4%), and foraminifera (2%) (Fig. 3.5).

Biological Communities

The small pockets of sediment in the Rock Bottom Facies support the growth of *Thalassia,* various corals, and algae. Many species of brown algae are attached to rocky substrates. In South Sound and John Bodden Bay these include *Dictyota* sp., *Padina jamaicensis,* and *Stypopodium zonale.* Some species of green algae also require these hard substrates for attachment. Included are *Dasycladus vermicularis, Udotea* sp., *Dicytosphaeria cavernosa,* and *Acetabularia* sp. Other genera of green algae include *Halimeda, Penicillus,* and *Avrainvillea asarifola.* The red alga *Jania adherens* inhabits protected depressions in the rocky substrate.

The Rock Bottom Facies hosts a high diversity of corals. Most are Scleractinia that assume encrusting, domal, branching, or knob-shaped growth forms. The most common of these are *Siderastrea radians, Siderastrea siderea, Diploria* sp., *Acropora cervicornis,* and *Acropora palmata.* Less common are *Poroites astreoides* and small heads of *Favia fagrum.* Octocorals are most common in the Rubble Facies and along the reef but *Pseudoplexaura* sp. and the purple corky sea finger (*Briarenum asbestinum*) also grow on the hard rock bottom near the reef where the water is clear.

Many spiny sea urchins inhabit crevices in the rock including *Tripneustes ventricosus* and *Diadema antillarum* (Fig. 3.6A). Sea urchins are more common in John Bodden Bay than in South Sound. Feather duster worms (*Bispira variegata*) are found on the hard substrate in the northeastern part of South Sound.

3.5 RUBBLE FACIES

The Rubble Facies is a 60 - 250 m wide zone that parallels the reef crest on the landward side, and almost completely covers John Bodden Bay (Fig. 3.1). The

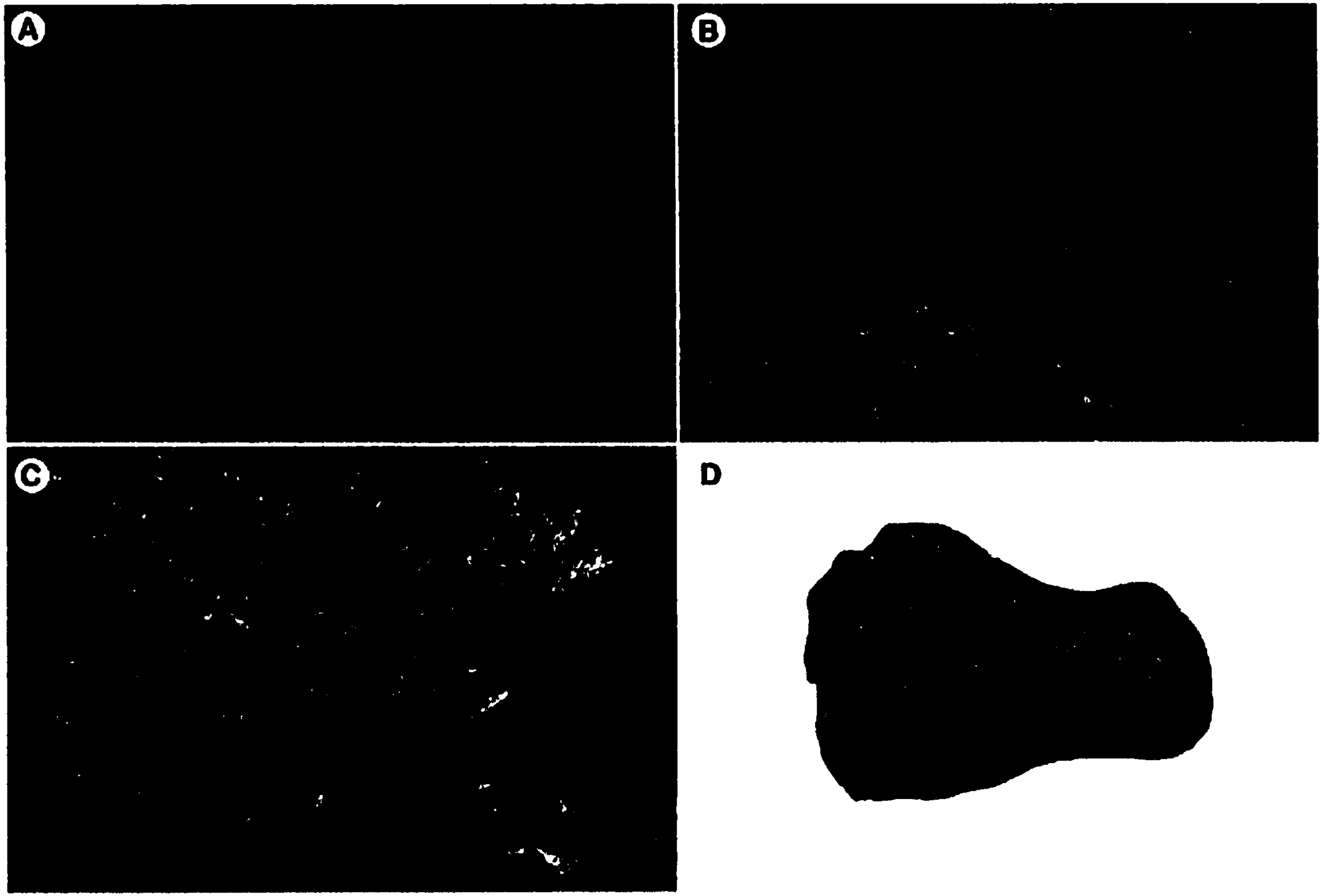

Fig. 3.6. **A)** Sea urchin (20 cm long) in the Rock Bottom Facies. **B)** Coral rubble in the Rubble Facies. **C)** *Acropora Palmata* (about 55 cm high) patch reef. **D)** Crocodile vertebra (2.5 cm long) from the Brown Algae Facies.

Rubble Facies predominantly consists of rubble blocks broken from corals along the reef (Fig. 3.6B) and washed shoreward by storm waves breaking over the reef crest. The smaller coral rubble blocks may form the nucleus of rhodoliths. Rhodoliths form as unattached rubble blocks are agitated, allowing for an even coating of red algae around the nucleus (Bosellini and Ginsburg 1971; Hills 1998). Although rhodoliths are also found in the Sand Facies of South Sound, they are most abundant in the Rubble Facies at the east end of the lagoon.

The Rubble Facies is floored by a hard substrate, but a thin sediment cover and pockets filled with sediment are common. Physical and chemical breakdown of the rubble is high. Water depth gradually shallows in the Rubble Facies, being anywhere from 10 cm deep near the reef crest to 100 cm deep where it extends closer to shore (Fig. 1.11). The Rubble Facies contains some local patches of Sparse *Thalassia*, Coral Heads, or Bare Sand Facies.

Sedimentology

The sediment of the Rubble Facies is bimodal, consisting of coarse sand and cobble-sized material. The coarse sand fraction is moderately sorted and slightly negatively skewed. Its mean grain size varies randomly with its position along the reef (Appendix B). The cobble-sized fraction, which is moderately sorted and near-symmetrical, is composed of coral rubble broken from the reef crest (Table 3.2).

Grain size decreases shoreward from the reef crest. At the reef crest, the mean grain size is -7.3ø (medium cobble) with a coarse sand and pebble matrix (Fig. 3.7A). There is much more cobble-sized material than sand. About 30 m behind the reef crest, the primary grain size decreases slightly to -7.1ø. The amount of sand matrix increases in the backreef area, approximately 70 m behind the reef crest. The coral rubble is pebble- to cobble-sized. The midreef zone is the best sorted (moderately well), and sorting decreases to moderate in the backreef and reef crest. Clay, at 0.3%, is almost non-existent in the Rubble Facies.

The shape of the cobbles and pebbles is most commonly bladed, especially in the midreef area (Fig. 3.7B). Discoidal and prolate shaped clasts are commonly found with the bladed clasts in both the backreef and reef crest. Spheroidal cobbles are rare. Most clasts are bladed because they are derived from *Acropora palmata*, the dominant coral at the reef crest (Blanchon *et al.* 1997). Other clasts were derived from *Montastrea annularis*, *Diploria* sp., *Acropora cervicornis*, *Siderastrea* sp., and *Millepora* sp. (Blanchon *et al.* 1997).

The grains of the sand-sized matrix of the Rubble Facies are predominantly composed of fragmented mollusks (57%). Other biotic components are coral pieces (14%), *Halimeda* (12%), foraminifera (8%), and red algae (7%) (Fig. 3.5). The degree of boring is high but micritization is low.

Biological Communities

The Rubble Facies contains many patch reefs, as well as individual corals (see Coral Head Facies). Besides corals, gorgonians and algae are also present. Abundant gorgonians are *Briareum asbestinum*, *Plexaura* sp., and *Gorgonia flabellum*. The brown algae *Dictyota* sp., *Stypopdium zonale*, *Turbinaria* sp., and *Padina jamaicensis* are attached to the rocky substrate and cobbles. Green algae are less abundant but include *Udotea*, *Halimeda*, *Acetabularia*, and *Penicillus*. *Homotrema rubrum* commonly encrusts the undersides of rubble. Biota covers 15 - 25% of the Rubble Facies, with the remainder being rock substrate or lithoclasts.

Nocturnal fauna living among the rubble include octopuses and fire worms. Sea urchins, gastropods, and fish bioerode the rubble pieces, which are also extensively bored.

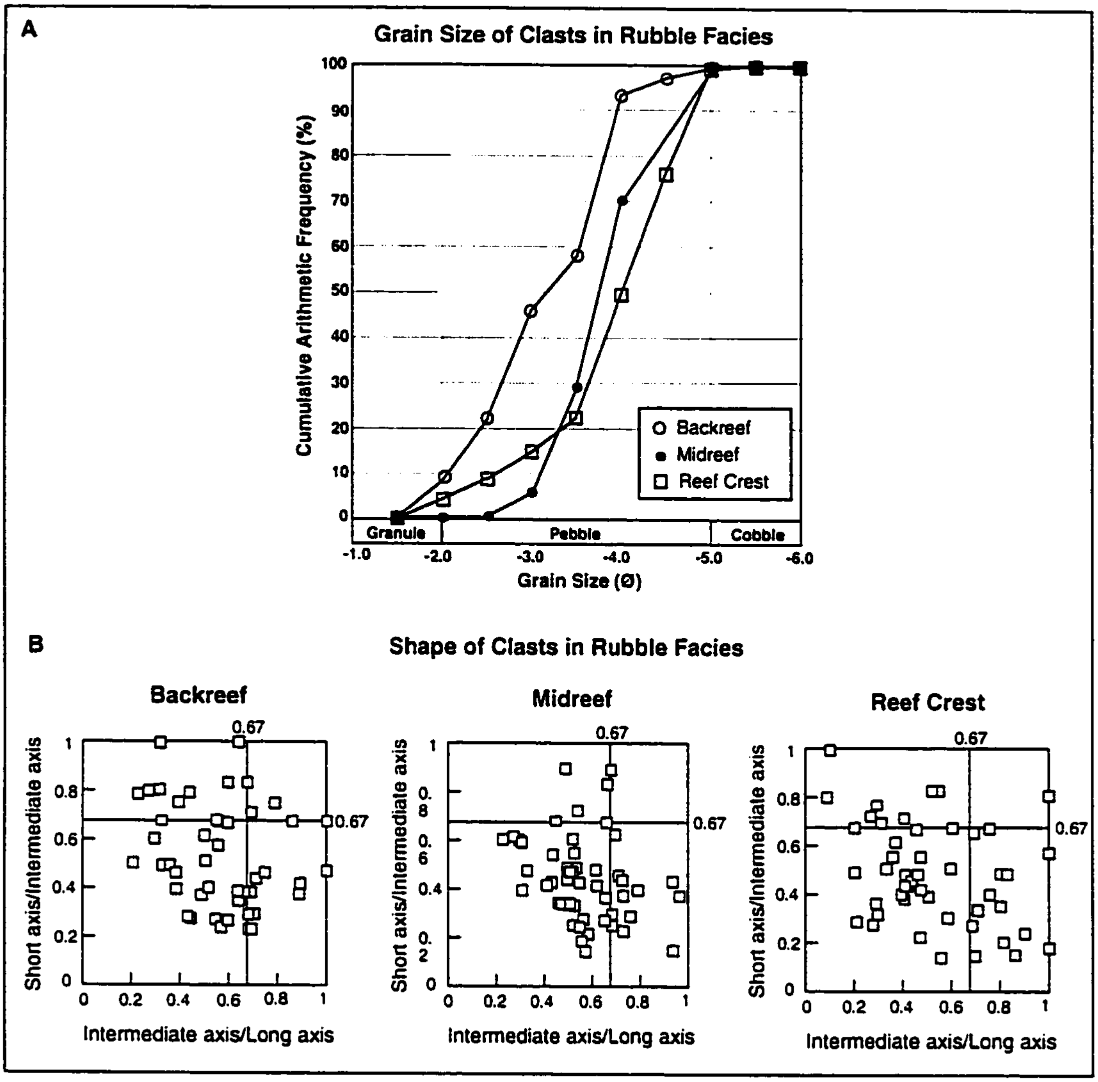

Figure 3.7. A) A comparison of the size of clasts in the backreef, midreef, and reef crest area of the Rubble Facies. B) A comparison of the shape of clasts in the backreef, midreef, and reef crest area of the Rubble Facies. Shape quadrants of the Zingg (1935) graph are shown in Fig. 2.2.

3.6 CORAL HEAD FACIES

Coral heads are grouped into their own facies because of the unique environment that they create. On the air photographs, they are round to irregularly-shaped clusters that are very dark-toned (Fig. 3.2). Individual coral heads and coral colonies are common in the Rubble Facies and less common in the Sand Facies. In South Sound, the number of coral heads increased significantly between 1971 and 1992. The coral colonies (patch reefs) grew around a nucleus of large dead *Acropora palmata* blocks, 4 to 5 feet high (Fig. 3.6C). Coral abundance and diversity gradually decreases shoreward of the reef crest.

Biological Communities

The patch reefs are covered with a diverse and abundant array of living corals and gorgonians. The most common are: *Porites porites, P. astreoides, Acropora palmata, A. cervicornis, Diploria* sp., *Siderastrea siderea, Gorgonia,* and *Briareum asbestinum. Porolithon pachydermum* encrusts the reefs, and many other indeterminate species of coralline algae are present. Free-standing corals are predominantly of the species *Siderastrea siderea, S. radians, Montastrea annularis, Agaricia agaricites, Favia fragrum, Millepora squarrosa, M. complanata, Colpophyllia natans,* and *Stephanocoenia michelinii.* Individual *Gorgonia* are also common.

3.7 BROWN ALGAE FACIES

The Brown Algae Facies is limited to a 5.9 ha patch in the northeastern part of South Sound (Fig. 3.1). Its lighter and more varying tone allows it to be distinguished from the surrounding *Thalassia* Facies on aerial photographs. The reflectance properties of this material is fairly low because the fine-grained sediment is water-saturated and organic-rich (Fig. 3.2). Numerous dark grey *Calianassa* mounds produce an irregular sediment surface topography. Bare sand and *Calianassa* mounds form 70% of the surface cover of the Brown Algae Facies, and algae covers the remaining 30%. This facies is surrounded by dense red mangroves (*Rhizophora* *mangle*) on the shoreward side.

Sedimentology

The finest grained sediment in South Sound is found in the Brown Algae Facies. It is a poorly sorted fine sand containing 14.3% silt and clay. There are fewer mollusk fragments in the sediment than in other facies and organic material, including roots, are common. Micritization of the grains is low, but most have been moderately bored (Table 3.2).

Biological Communities

One random square metre of the Brown Algae Facies encompasses 4 *Calianassa* mounds, 7 *Penicillus*, and 37 *Halimeda* (Appendix B). Most of the *Penicillus* and *Halimeda* grow individually, rather than in clusters. The sediment surface is covered by a blanket of unidentified thin, fibrous, and furry brown algae. Where the blanket brown algae engulfs the green algae, algal mounds, which are 4 m across and 1 m high, may be formed. Small, attached, *Siderastrea radians* are commonly associated with these algal mounds.

Mollusks found exclusively in the Brown Algae Facies include *Neritina virginea, Pitar fulminata, Chione undulata,* and *Cerithium variable. Chione cancellata* is also common in the Brown Algae Facies.

Core 7, taken six metres from the shoreline in the Brown Algae Facies, contains a crocodile vertebra (Fig. 2.1; Fig. 3.6D). This was found 26 cm down from the sediment surface, in a medium grey, coarse-grained carbonate sand, containing numerous *Halimeda* plates. This is a crocodylian dorsal vertebra, from an adult individual. The species is impossible to determine from this vertebra (Dr. Xiao-Chun, Royal Tyrell Museum, per. comm.).

Crocodiles have been extirpated on Grand Cayman since the late nineteenth century. Fossil crocodile remains have previously been recovered from six sites on Grand Cayman, and the most recent date was 375 ±60 yBP (Morgan *et al.* 1993). All fossil remains were found in dark brown to black, organic-rich, peaty sediments, representing a mangrove swamp or coastal lagoon environment. The bones belong to *Crocodylus rhombifer*, a modern Cuban crocodile presently inhabiting freshwater marshes and swamps. Its widespread fossil distribution on Grand Cayman indicates that this species may have had wider environmental tolerances than it does now (Morgan *et al.* 1993).

ASSESSING THE ACCURACY OF DIGITAL IMAGE ANALYSIS

3.8 ACCURACY ASSESSMENT

The accuracy of the results of the facies delineation in South Sound by digital image analysis depends on the quality of information derived from the image analysis process. Quantitative accuracy assessment involves the comparison of the facies on the computer-generated digital map with the facies at the same location in the lagoon. A good accuracy assessment will satisfy the following criteria:

- the probability of accepting a low accuracy map will be low,
- the probability of accepting a high accuracy map will be high,
- biases will be kept to a minimum, and
- a minimum number of ground sample points will be required (Ginevan 1979; Fitzpatrick-Lins 1981; Aronoff 1982; Congalton 1988).

Sample Size and Sampling Technique

The rule of thumb is that there should be a minimum of 50 ground (reference) sample points per class to minimize sampling biases and to increase precision at a specified significance level (Hord and Brooner 1976; Hay 1979; Congalton 1991; Congalton and Green 1999). This is, however, a generalization and a more appropriate number of samples may be used.

To prevent bias toward one class or another, weighted sampling was employed. Weighted sampling allows the number of samples collected per class to be proportional to the area that the class occupies (Fitzpatrick-Lins 1981; Sánchez-Azofeifa 1996). Therefore, a class with a small aerial extent is not overemphasized. Also, the number of samples in a class can be increased or decreased to reflect the relative importance of that class (Hay 1979; Congalton 1991). The number of samples taken per class should be arrived at by careful consideration of the mapping objectives and the inherent variability in each class.

A multinomial distribution will provide the equation needed to determine an appropriate overall sample size for building an error matrix. A multinomial distribution must be used for the accuracy assessment of South Sound because a binomial distribution will only consider a correct or incorrect option for the samples in a class. For South Sound, a sample can be in one of ten classes. The multinomial equation used was originally presented by Tortora (1978) but is summarized in Congalton and Green (1999).

The number of samples for the entire error matrix will depend upon the absolute precision of the classification (b_i) where i represents the i^{th} class where $i = 1, 2, ..., k$. A precision of 5% is commonly used. Π_i is the ratio of the map area that this particular class makes up and B is the upper 95th percentile determined from a Chi square table with 1 degree of freedom, so the value for $B = 7.568$. The sample size to be determined is *n*. Therefore:

$$n = B\,\Pi_i\,(1 - \Pi_i)/b_i^2$$

For South Sound, a minimum of 423 samples was determined from this equation to be taken for the entire error matrix and each class was then weighted to the total area which it represents (Table 3.3).

The sampling technique used in the field was systematic. Traverses were run perpendicular to the shoreline, with the first sample station being selected randomly. All subsequent sample stations were than taken at an 8 m interval from the one before it. This sampling technique distributes the samples fairly uniformly over the entire lagoon, but a disadvantage is that all areas of the lagoon do not have an equal chance of being selected once the first point has been established (Cochran 1963; Dalton *et al.* 1975; Freund and Williams 1977; Silk 1979; Congalton 1988; Tongpenyai 1989).

Error Matrix

An error matrix or contingency table was constructed to compare information from the reference data, which is the data obtained from field work in the lagoon, to the classified data from the produced digital images (Table 3.4). The matrix is an array of numbers in rows and columns reflecting the number of samples assigned to a particular class which correspond between the reference data and the classified data (Hay 1979; Aronoff 1982; Congalton and Mead 1983; Jensen 1986; Congalton 1991; Congalton and Green 1999). Any numbers along the diagonal of the matrix show that the classes were the same for both the reference and classified data. Any numbers elsewhere in the matrix show that the classes did not correspond between the two.

For an accuracy assessment to be useful, the reference data in the columns must be assumed to be correct. Objectivity and consistency were maintained by keeping the reference data independent from the classified data. This was most easily accomplished by collecting the field data one year before the classification was performed. In the lagoon, all data were collected over four consecutive weeks in a careful, consistent, and controlled manner.

The overall accuracy is the sum of the areas correctly classified along the diagonal of the matrix divided by the total number in the error matrix. The overall accuracy in South Sound was found to be 90% (501/554*100) (Table 3.5). Milazzo (1980), Jensen (1986), and Congalton and Green (1999) suggested that an overall accuracy value above 85% is acceptable and the U. S. Geological Survey and Anderson (1971), Anderson *et al.* (1972), and Anderson *et al.* (1976) recommended at least an 85 - 90% accuracy level. The accuracy of the assessment of South Sound meets these requirements.

The overall accuracy can be supplemented by the producer's accuracy and the user's accuracy, which is calculated for each individual class (Table 3.5). The producer's accuracy is arrived at by dividing the total number of correct classes for each facies by its column total. From this, the errors of omission can be recognized. Omission errors are created when a sample is excluded from a class to which it actually belongs. Conversely, the user's accuracy is the total number of correct classes for each facies divided by the row total. It is indicative of the probability of a sample classified on the map actually representing this class on the ground (Aronoff 1982; Jensen 1986; Congalton 1991; Sánchez-Azofeifa 1996; Congalton and Green 1999). This results in a measure of the commission error, or erroneously including a sample in a class to which it does not belong. This means that, for example, 85% of the Dense *Thalassia* Facies has been correctly identified as the Dense *Thalassia* Facies, but 91% of the areas called Dense *Thalassia* on the classified map are actually

Table 3.3. Minimum number of samples required per class in accuracy assessment.

Facies	**Maximum Number of Samples from Weighted Multinomial**
Very Dense Thalassia	*10*
Dense Thalassia	*70*
Medium Thalassia	*71*
Sparse Thalassia	*66*
Rubble	*42*
Coral Heads	*26*
Brown Algae	*7*
Sparsely Vegetated Sand	*34*
Bare Sand	*52*
Rock Bottom	*45*
Total	**423**

Dense *Thalassia* on the ground. It appears the confusion resulted from discriminating between the Dense *Thalassia* Facies and the Very Dense *Thalassia*, Medium *Thalassia*, and Sparse *Thalassia* Facies on the map. Six times on the map the Dense *Thalassia* Facies was mistaken for the Medium *Thalassia* Facies and four times it was mistaken for the Very Dense *Thalassia* Facies. This error is understandable because the tones of these facies are very similar and they are spatially adjacent to each other. The largest discrepancy was in the user's accuracy of the Very Dense *Thalassia* Facies at 76%, suggesting that the Very Dense *Thalassia* Facies on the classified map was not always Very Dense *Thalassia* on the ground.

Confidence Level

The confidence level of the overall, producer's, and user's accuracies exceeding the 85% accuracy criterion can now be determined. A multinomial confidence limit equation must by used since there are more than two classes in the image analysis of South Sound. This equation was based on the short version of the multinomial confidence distribution interval equation in Goodman (1965), originally presented by Quesenberry-Hurst (1964), after being applied to remote sensing.

The upper and lower 95% confidence limit for each class is estimated from the following multinomial distribution:

$$\Pi_i^- = p_i - [A\,p_i\,(1-p_i)/\mathrm{N}]^{1/2}$$

$$\Pi_i^+ = p_i + [A\,p_i\,(1-p_i)/\mathrm{N}]^{1/2}$$

where Π_i is the probability that a sample will fall in the i^{th} cell where $i = 1, 2, ..., k$; A is the upper 95th percentile point of the Chi square distribution with one degree of freedom; and $p_i = n_i/\mathrm{N}$. n_i is the number of samples falling in the i^{th} cell and N is the total sample size. The upper and lower 95% confidence limits for both the producer's and user's accuracies indicate that the true map accuracy is, with 95% confidence, in the range shown (Table 3.5). For example, the true producer's accuracy for the Dense *Thalassia* Facies with 95% confidence is between 81% and 89%.

Tau Coefficient

Another measurement of the accuracy of data in the error matrix is the Tau Coefficient (Table 3.5). Ma and Redmond (1995) indicated that the Tau Coefficient is an extremely useful measure of classification accuracy in remote sensing. The

Table 3.4. Error matrix for the accuracy assessment of the digital image analysis of South Sound.

		Reference Data										
	Facies	*Very Dense Thalassia*	*Dense Thalassia*	*Medium Thalassia*	*Sparse Thalassia*	*Rubble*	*Coral Heads*	*Brown Algae*	*Sparsely Vege. Sand*	*Bare Sand*	*Rock Bottom*	**Row Total**
Classified Data	*Very Dense Thalassia*	*13*	*4*								*2*	*17*
	Dense Thalassia		*72*	*2*					*3*		*5*	*79*
	Medium Thalassia		*6*	*79*					*2*		*2*	*92*
	Sparse Thalassia		*3*		*66*		*4*		*3*	*1*		*79*
	Rubble					*50*						*50*
	Coral Heads						*30*		*2*			*32*
	Brown Algae							*50*				*50*
	Sparsely Vege. Sand				*2*				*34*		*4*	*40*
	Bare Sand				*3*	*2*				*52*		*57*
	Rock Bottom					*2*	*1*				*55*	*58*
	Column Total	*13*	*85*	*81*	*71*	*54*	*35*	*50*	*44*	*53*	*68*	*554*

overall accuracy does provide a quick and easy assessment, but it does not take into account the proportion of agreement between classes that is due to chance alone, so classification accuracy tends to be overestimated (Congalton and Mead 1983; Congalton *et al.* 1983; Rosenfield and Fitzpatrick-Lins 1986; Ma and Redmond 1995). The Tau Coefficient compares the classification against a random assignment, to determine what the improvement is (Ma and Redmond 1995). For error matrices constructed using an unsupervised classification, such as was done for South Sound,

Table 3.5. Calculations of individual class and overall accuracies for the accuracy assessment of South Sound. All tables values are in percent.

Accuracy \ Facies	Very Dense Thalassia	Dense Thalassia	Medium Thalassia	Sparse Thalassia	Rubble	Coral Heads	Brown Algae	Sparsely Vege. Sand	Bare Sand	Rock Bottom
Producer's Accuracy	100	85	98	93	93	86	100	77	98	81
Errors of Omission	0	15	2	7	7	14	0	23	2	19
User's Accuracy	76	91	86	84	100	94	100	85	91	95
Errors of Commission	24	9	14	16	0	6	0	15	9	5
Producer's Upper 95% Confidence Limit	100	89	99	96	96	91	100	83	100	88
Producer's Lower 95% Confidence Limit	100	81	96	90	89	80	100	71	96	73
User's Upper 95% Confidence Limit	86	95	89	88	100	98	100	91	95	98
User's Lower 95% Confidence Limit	76	87	82	79	100	90	100	80	88	92

Overall Accuracy: 90%

Tau Accuracy: 89%

the initial chance of a sample belonging to any class is equal, so the random agreement (P_r) is determined by the number of classes (M):

$$P_r = 1/M$$

The classes in this situation are based on the equal probability of a sample being in any class, so the Tau Coefficient is T_e. Then:

$$T_e = P_o - P_r / 1 - P_r$$

where P_r is as defined above and P_o is the percentage agreement, or the overall accuracy. For South Sound, since $P_o = 90\% = 0.90$ and $M = 10$, $T_e = (0.90 - 0.1)/1 - 0.1 = 89\%$. Therefore, 89% more samples were classified correctly than would have been expected by random assignment.

3.9 SYNOPSIS

South Sound is divided into six facies based on tonal, sedimentological, and biotic characteristics. The division and distribution of these facies can be confidently accepted, with an overall accuracy of 90% and a Tau accuracy of 89%.

Grain size distribution of the sediment in the lagoon is near-Gaussian, because skewness is always minimal. The facies have a unimodal size distribution, except for the Rubble Facies, which has a cobble-sized mode and a coarse sand mode. Sediment size is coarsest near the reef crest in the Rubble Facies and becomes progressively finer-grained in the Rock Bottom Facies, *Thalassia* Facies, and Sand Facies. The finest mean grain size is found in the Brown Algae Facies in the northeast corner of the lagoon. The sorting of the sediment in South Sound is poor. Only the Rubble Facies and Rock Bottom Facies are moderately sorted.

Sediment grains are commonly composed of mollusks and *Halimeda*. Locally abundant are foraminifera, red algae, and coral fragments. Only the Brown Algae and *Thalassia* Facies have significant roots in the sediment. On a larger scale, the *Thalassia* Facies has the most dense covering of flora, but the Rock Bottom Facies hosts the greatest diversity of plant species.

CHAPTER 4

ARCHITECTURE OF SOUTH SOUND

4.1 INTRODUCTION

The descriptions of sediments, biota, and relative position of each of the facies in South Sound provide the basis for understanding the lagoonal conditions as found in 1992. By comparing the distribution and aerial coverage of the facies in 1992 with those of 1971, however, it becomes evident that the lagoonal system is constantly changing. The biota of each facies responds to the dynamic conditions by retreating from areas that are becoming unfavourable for habitation, and expanding into areas that are more suitable. As a result of the changes in sediment-producers, sediments also change. Commonly, the migration of facies is accompanied by its fragmentation, or, less commonly, its agglomeration into larger and fewer patches. The trends in facies adjustment allows the evolution of the lagoon to be determined over a short period of time.

4.2 SURFACE DISTRIBUTION OF FACIES IN 1992

The position of the lagoonal substrates on the aerial photographs and on the classified maps indicates that there is a systematic distribution of facies across South Sound (Fig. 3.1, 3.2). Thus, from the shoreline to the reef crest, the facies are: Very Dense *Thalassia* Facies, Dense *Thalassia* Facies, Medium *Thalassia* Facies, Sparse *Thalassia* Facies, Sparsely Vegetated Sand Facies, Bare Sand Facies, Coral Head Facies, and Rubble Facies. The Rock Bottom and Brown Algae Facies disrupt this typical pattern in the far west and far east areas of South Sound, respectively (Fig. 3.1). The facies are found in fragmented patches that, when combined together, form continuous belts.

4.3 COMPARISON OF FACIES DISTRIBUTION WITH PREVIOUS WORK

Rigby and Roberts (1976) produced a facies distribution map of South Sound from data acquired during swimming traverses in 1967 (Fig. 4.1A). Although the facies are more simplistic than those derived from computerized image analysis, the general patterns remain essentially unchanged. The major facies determined by Rigby and Roberts (1976) were the: 1) *Thalassia* Facies, 2) Sand Facies, 3) Coral Facies, and 4) Brown Algae Facies. The *Thalassia* Facies paralleled the shoreline and grew in isolated patches in the centre of the lagoon. It was further divided into the inner belt, with high, dense *Thalassia*; the intermediate belt, offshore from the first, with a higher diversity of corals and algae; and the deeper water *Thalassia* composed of shorter, more widely spaced plants. This can be equated with the Very Dense/ Dense *Thalassia*, Medium *Thalassia*, and Sparse *Thalassia* Facies of this study, both by spatial distribution and biotic composition. The Bare Sand and *Calianassa*-mounded Sand Facies is similar to the Bare Sand Facies and Sparsely Vegetated Sand Facies of this study, although the former has been agglomerated into one large patch in the centre of South Sound (Fig. 3.1). The coral, rubble, and reefal areas defined by Rigby and Roberts (1976) are similar to those in this study, except that the rubble in the west part of South Sound was named after the dominant coral species, *Montastrea annularis*. The Brown Algae Facies remains in the northeast corner of South Sound, but Rigby and Roberts (1976) included sand-covered areas with filamentous brown algae in this facies, increasing its aerial coverage.

Tongpenyai (1989) and Tongpenyai and Jones (1991) produced a facies map of South Sound using a combination of field work and manual and computer-automated image analysis techniques (Fig. 4.1B). These facies were the: 1) Dense *Thalassia* Facies, 2) Less Dense *Thalassia* Facies, 3) Transition Zone Facies, 4) Coral Facies, 5) Brown Algae Facies, and 6) Sand Facies. The facies of Tongpenyai (1989) and Tongpenyai and Jones (1991) are very similar in distribution and content to those defined in this study, with the following exceptions:

1. their facies are less fragmented and have larger patch sizes;
2. their Rubble Facies (Coral Facies) was underestimated with respect to this study;
3. their Brown Algae Facies was overestimated, and the patch in the northeast part of the lagoon was not distinguished (Fig. 4.1B).

Even though different image analysis techniques were used for these studies, similar results were produced. The level of detail and confidence, however, gradually increased with more modern analysis techniques.

4.4 SUBSURFACE FACIES SEDIMENTOLOGY AND DISTRIBUTION IN 1992

The distribution of the subsurface facies can only be recognized locally because very few cores could be obtained. This is due to the relatively thin sediment cover in South Sound, with the average sediment thickness being 25 cm. There are only three small patches of thick sediment accumulation in the lagoon: in the northeast, where

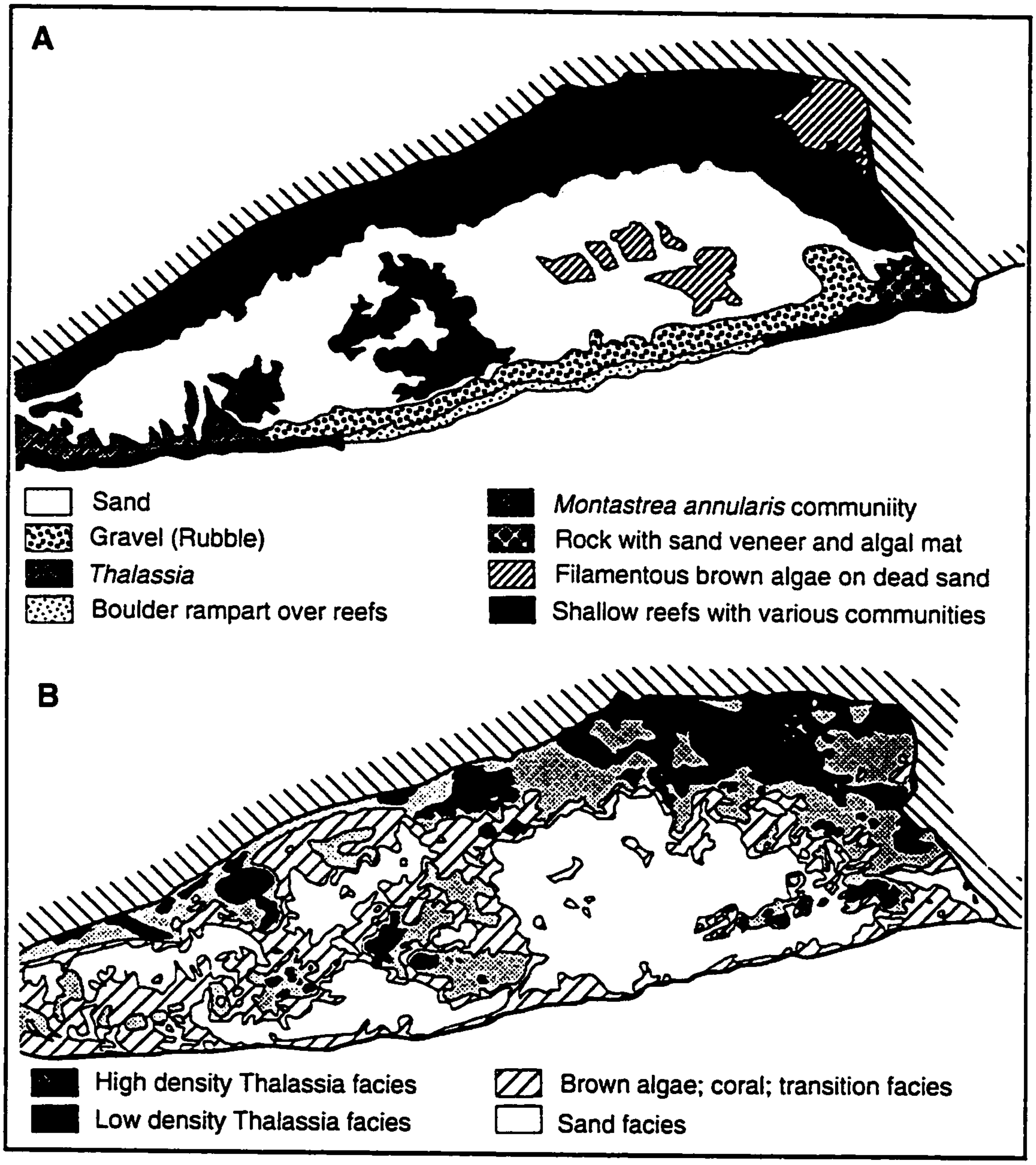

Figure 4.1. Comparison of facies maps of South Sound as produced by: **A)** Rigby and Roberts (1976), and **B)** Tongpenyai (1989) and Tongpenyai and Jones (1991), Modified from Tongpenyai and Jones (1991).

the sediment is up to 120 cm thick; in the centre of the lagoon; and at the edge of the rubble zone in the west (Fig. 4.2). In the central part of the lagoon the sediment is up to 90 cm thick, and a lobe in the west is up to 56 cm thick. The thickest sediment accumulation is in the northeast, 80 m from the shoreline in an organic-rich mangrove swamp area, where many of the cores were obtained (Fig. 2.1). John Bodden Bay only has a 1 - 3 cm thick sediment cover, and is underlain by a hard, rocky and rubbly substrate.

Subsurface sediments have sedimentological and compositional characteristics similar to surface sediments, but some of the subsurface facies reflect a local shift of the surface facies over time. Cores taken in the Dense *Thalassia* Facies are formed almost entirely of a homogenous skeletal sand containing *Halimeda*, red algae, fragmented mollusks, and foraminifera. The deepest core in the Dense *Thalassia* Facies encountered an organic-rich peat with roots at 54 cm (Fig. 4.3). Core SSC6, taken in Medium *Thalassia* Facies, also contains the homogenous skeletal muds of the Dense *Thalassia* Facies at 4 cm, but is capped by a medium- to coarse-grained carbonate sand of the Medium *Thalassia* Facies with abundant *Thalassia* roots and rhizomes.

The subsurface sediment in the Brown Algae Facies is composed of a medium grey, medium- to fine-grained carbonate sand with whole and fragmented *Halimeda* plates, gastropods, and bivalves. Between 34 - 44 cm depth is a thick black to brown organic-rich peat with structures of vegetal matter. The woody material and roots are commonly vertically-oriented, thin, and fibrous in texture. Flame and load structures at the top contact emphasize the soft consistency of the peat. The cores that are taken

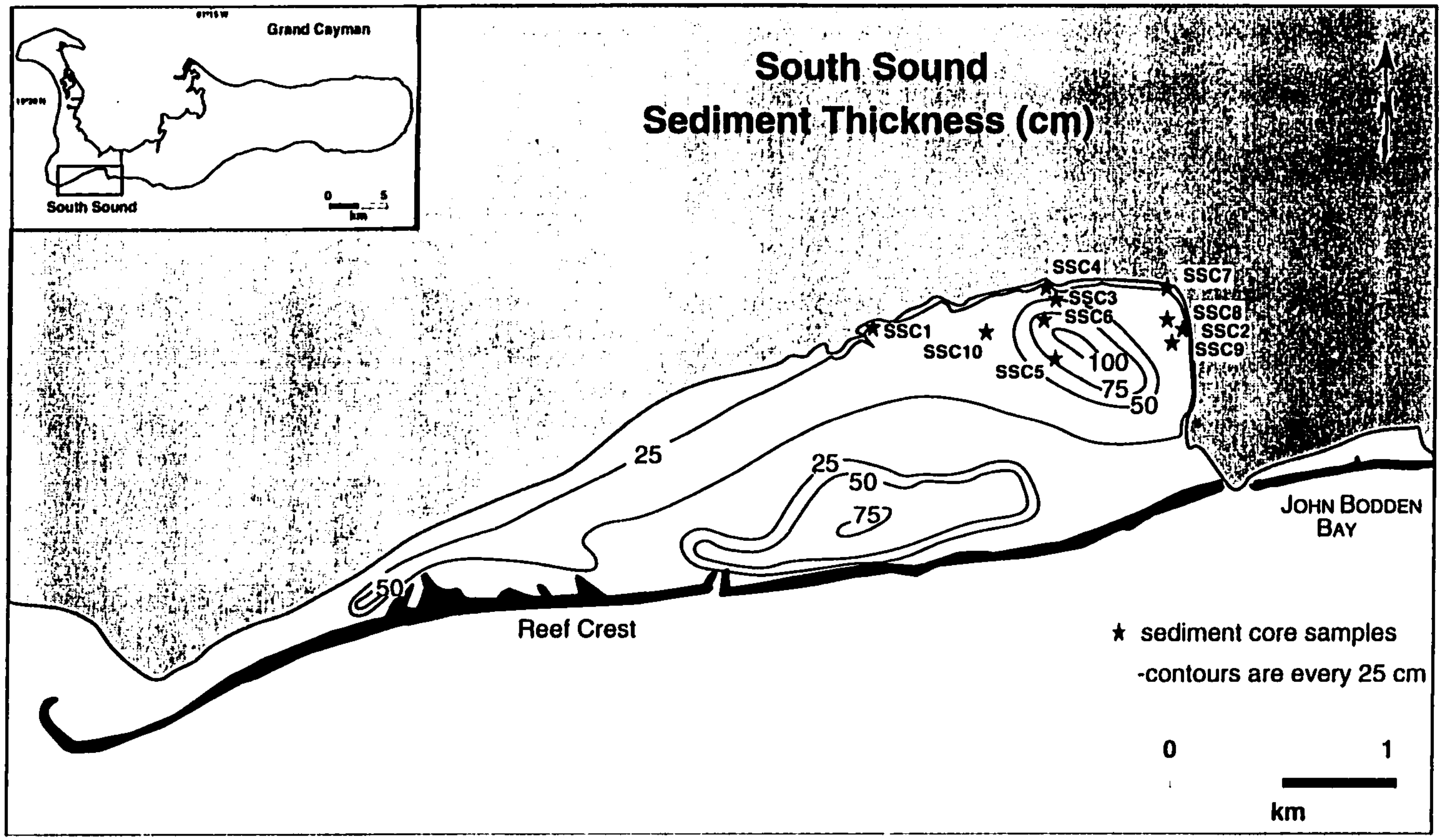

Figure 4.2. Sediment thickness of South Sound.

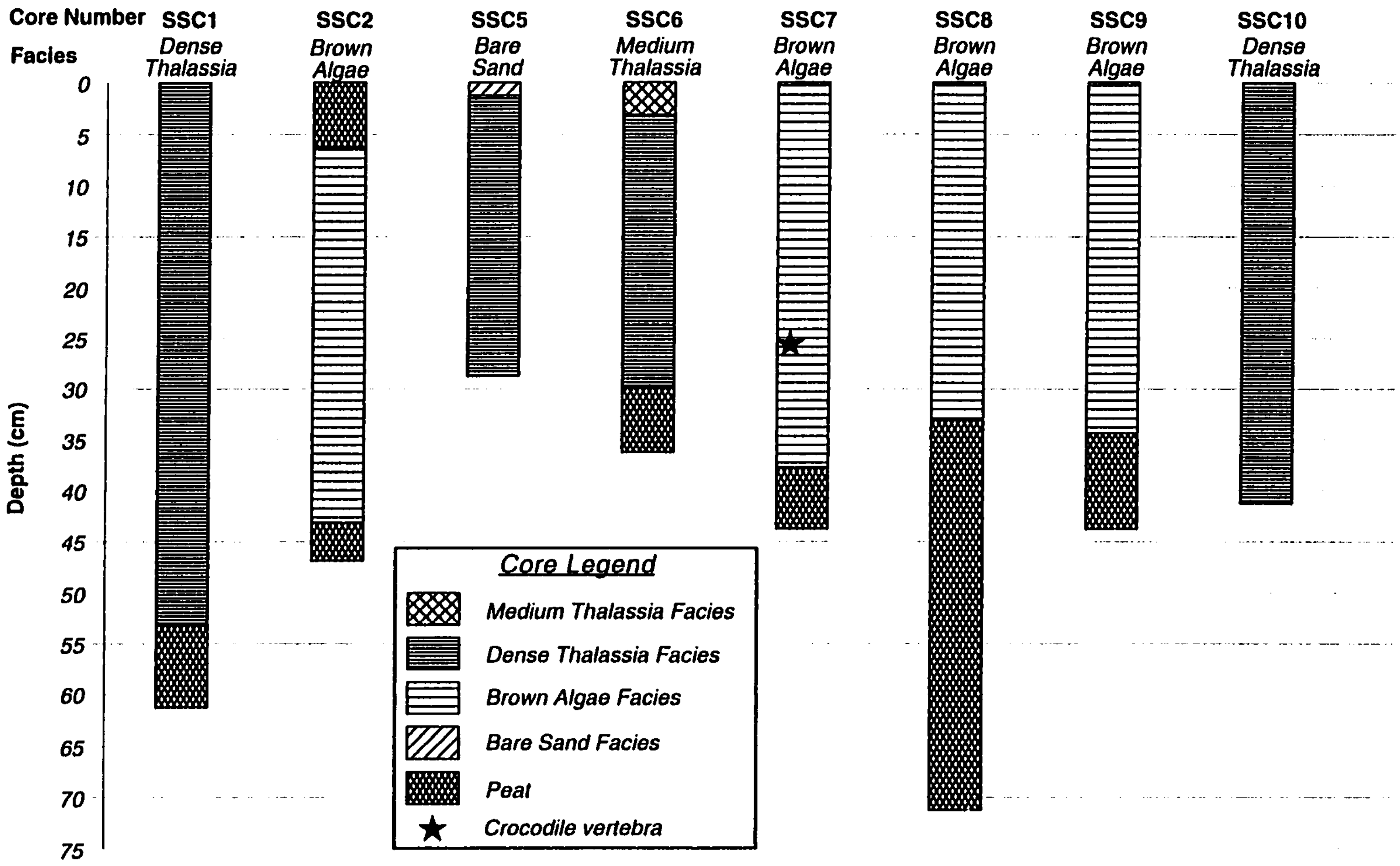

Figure 4.3. Lithology of loose sediment cores taken from various facies in South Sound.

closest to the shore have the most roots and the highest organic content. Cores taken in the Brown Algae Facies are composed of this facies throughout their length (Fig. 4.3).

Core SSC5, taken from a 40 m diameter sand patch in the Sand Facies, is composed of a tan-coloured, medium-grained, homogenous skeletal sand which represents the Dense *Thalassia* Facies (Fig. 4.3). It is capped by 2 cm of the Bare Sand Facies, a yellow to buff, medium-grained sand.

4.5 CHANGES IN FACIES BETWEEN 1971 AND 1992

During the 21 years between 1971 and 1992, there were some substantial changes in the area and distribution of facies in South Sound and John Bodden Bay (compare Figs. 3.1, 3.2, 4.4, and 4.5). The most significant change was in the *Thalassia* Facies which increased in area by 17.3% (Table 4.1). Most of this increase was in the central part of South Sound and was predominantly at the expense of sand, which decreased in area by 17.1%. *Thalassia* also expanded into the Brown Algae Facies in the northeastern part of the lagoon, causing it to be reduced in area by 0.6% (Fig. 4.6, 4.7, and Table 4.1). In the western outlet of South Sound, the *Thalassia* increase came at the expense of the Rock Bottom Facies (compare Fig. 3.1 and 4.4). Medium density *Thalassia* (250 - 500 plants/m^2) showed the largest increase in area (+ 7.3%) and both the Very Dense and Sparse *Thalassia* increased by 2.1%. The *Thalassia* increase occurred over 21 years, so coverage expanded by a rate of about 0.8% per year, covering an additional 57, 700 m^2/year.

The amount of *Thalassia* increase is similar to that determined in previous

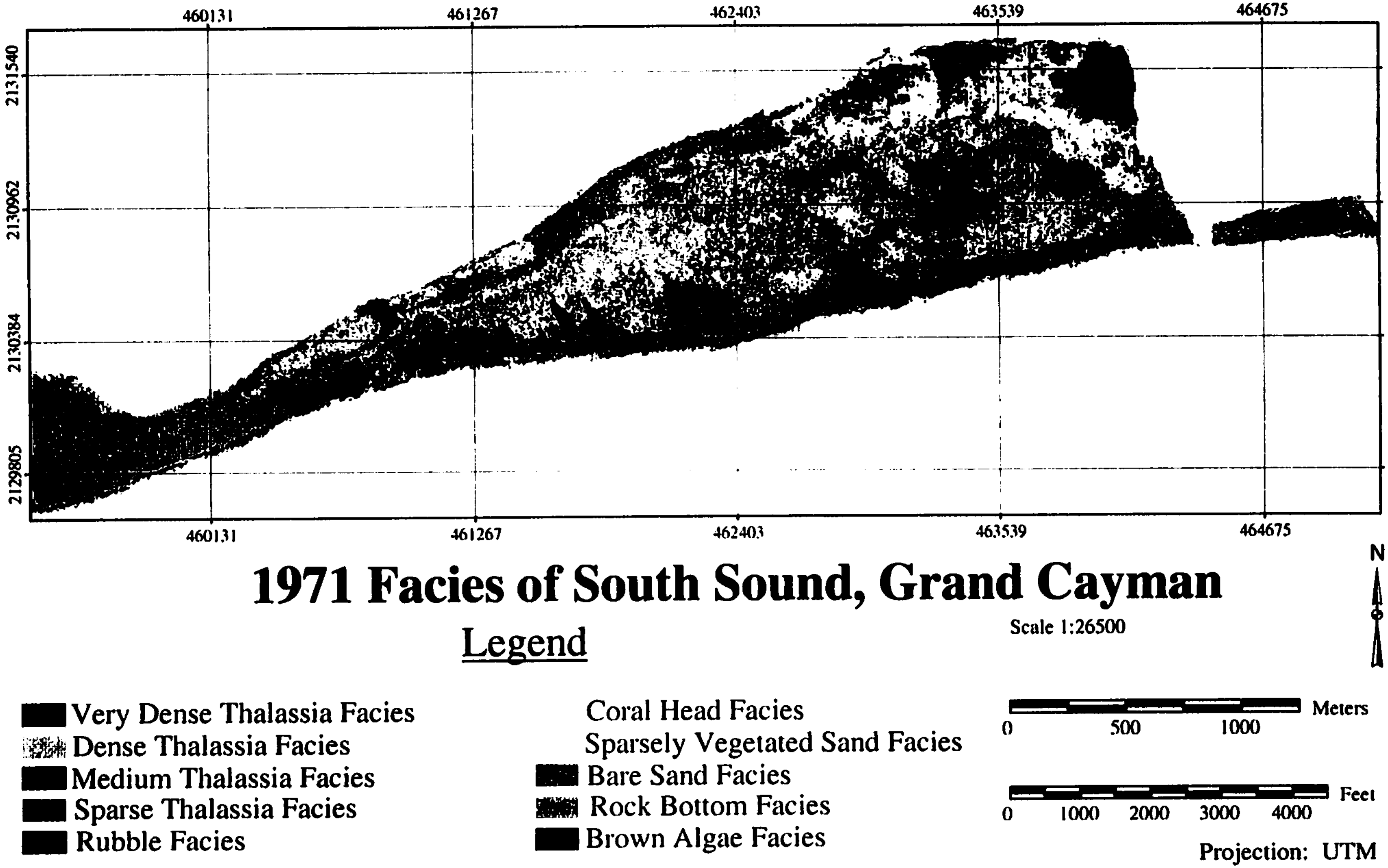

Figure 4.4. Classified 1971 facies map of South Sound.

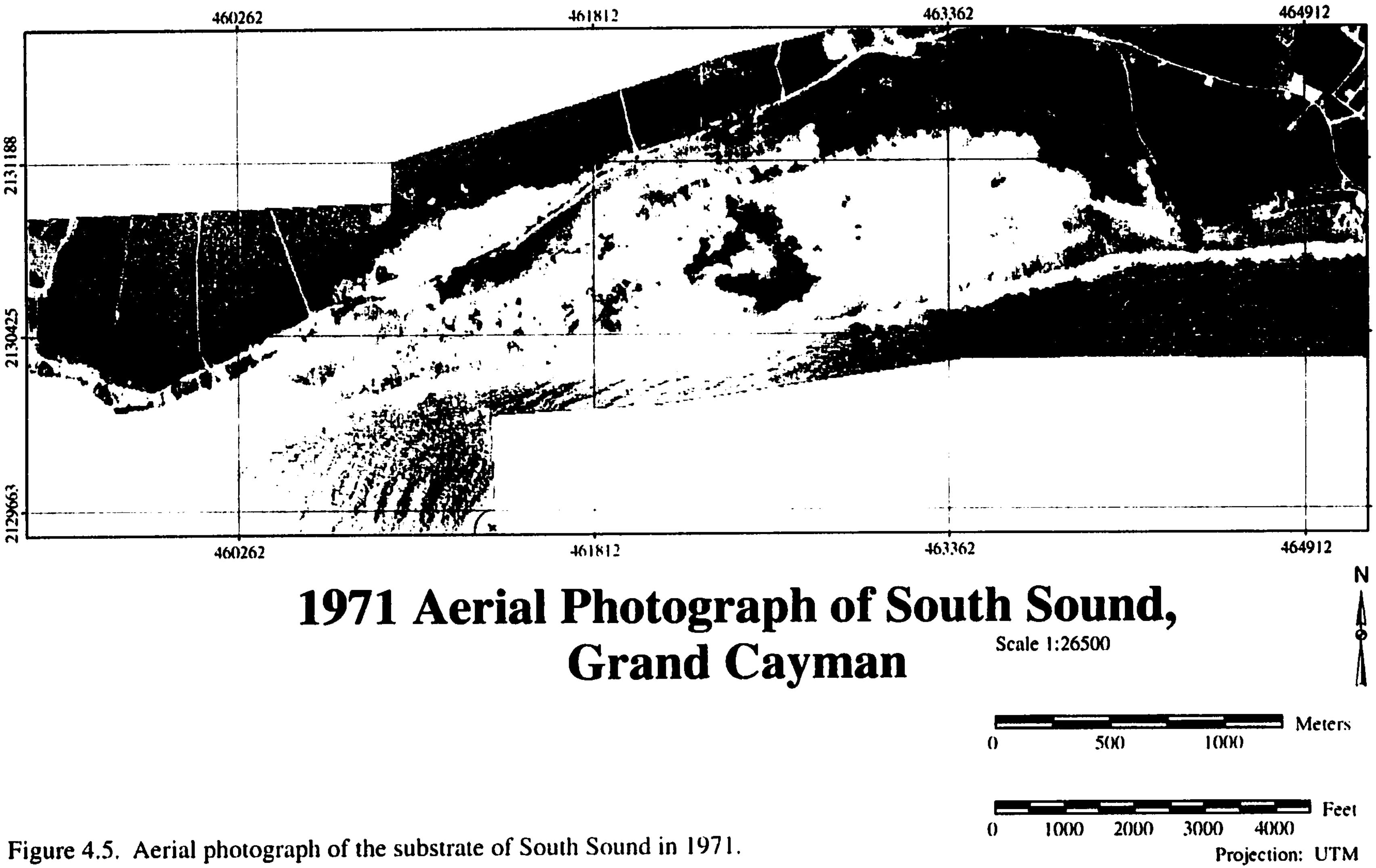

Figure 4.5. Aerial photograph of the substrate of South Sound in 1971.

Table 4.1. Aerial extent of facies in South Sound and John Bodden Bay, 1971 and 1992.

Facies	1971 Area (m^2)	1971 % Area	1992 Area (m^2)	1992 % Area	% Area Change
Very DenseThalassia	7040	0.2	78 136	2.3	+2.1
Dense Thalassia	386 259	10.8	567 560	16.6	+5.8
Medium Thalassia	340 439	9.5	576 053	16.8	+7.3
Sparse Thalassia	479 841	13.4	531 808	15.5	+2.1
Rubble	458 149	12.7	338 722	9.9	-2.8
Coral Heads	24 536	0.7	210 329	6.1	+5.4
Brown Algae	83 300	2.3	59 189	1.7	-0.6
Sparsely Vege. Sand	440 283	12.3	274 467	8.0	-4.3
Bare Sand	904 604	25.2	423 194	12.4	-12.8
Rock Bottom	463 148	12.9	364 573	10.7	-2.2

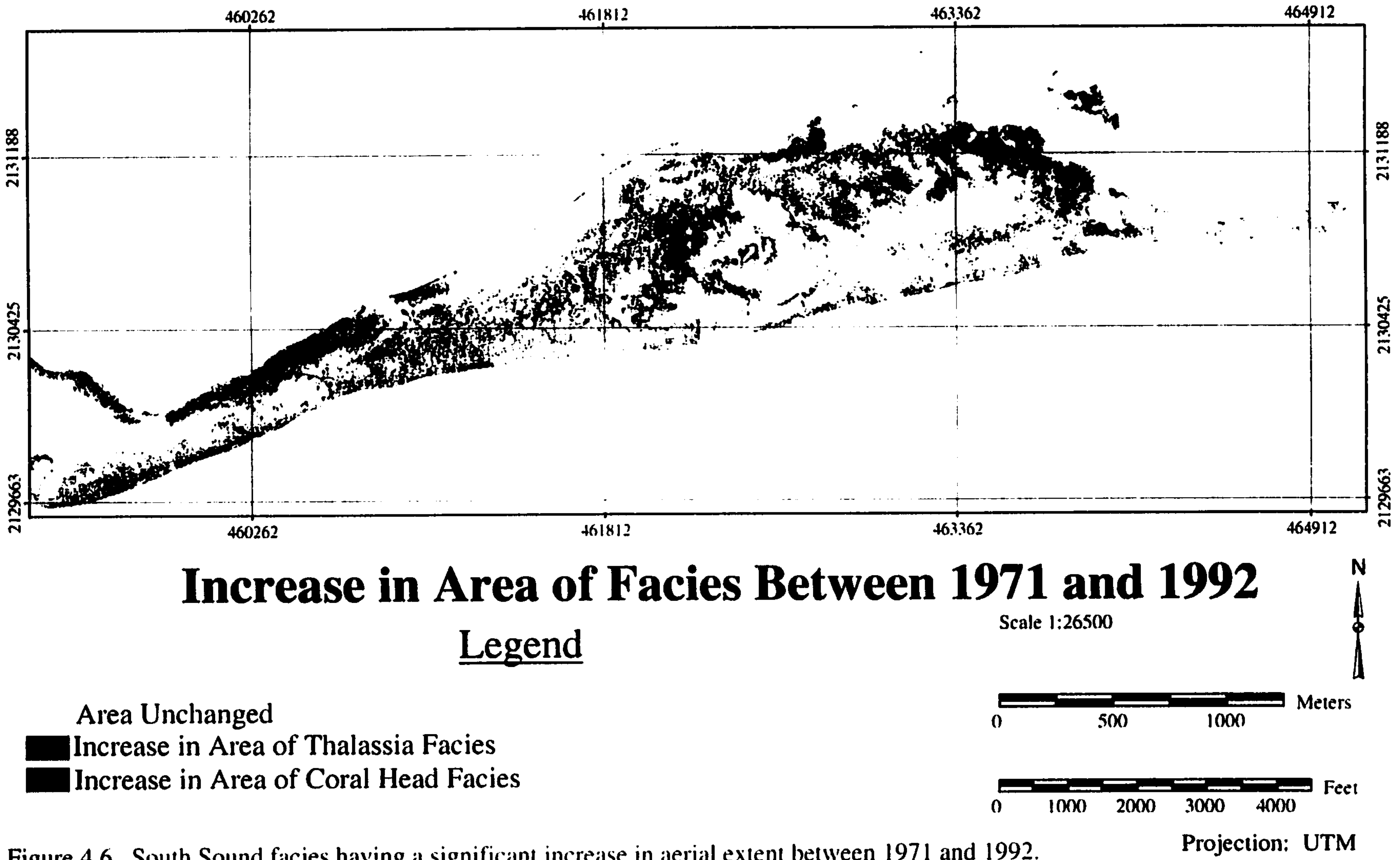

Figure 4.6. South Sound facies having a significant increase in aerial extent between 1971 and 1992.

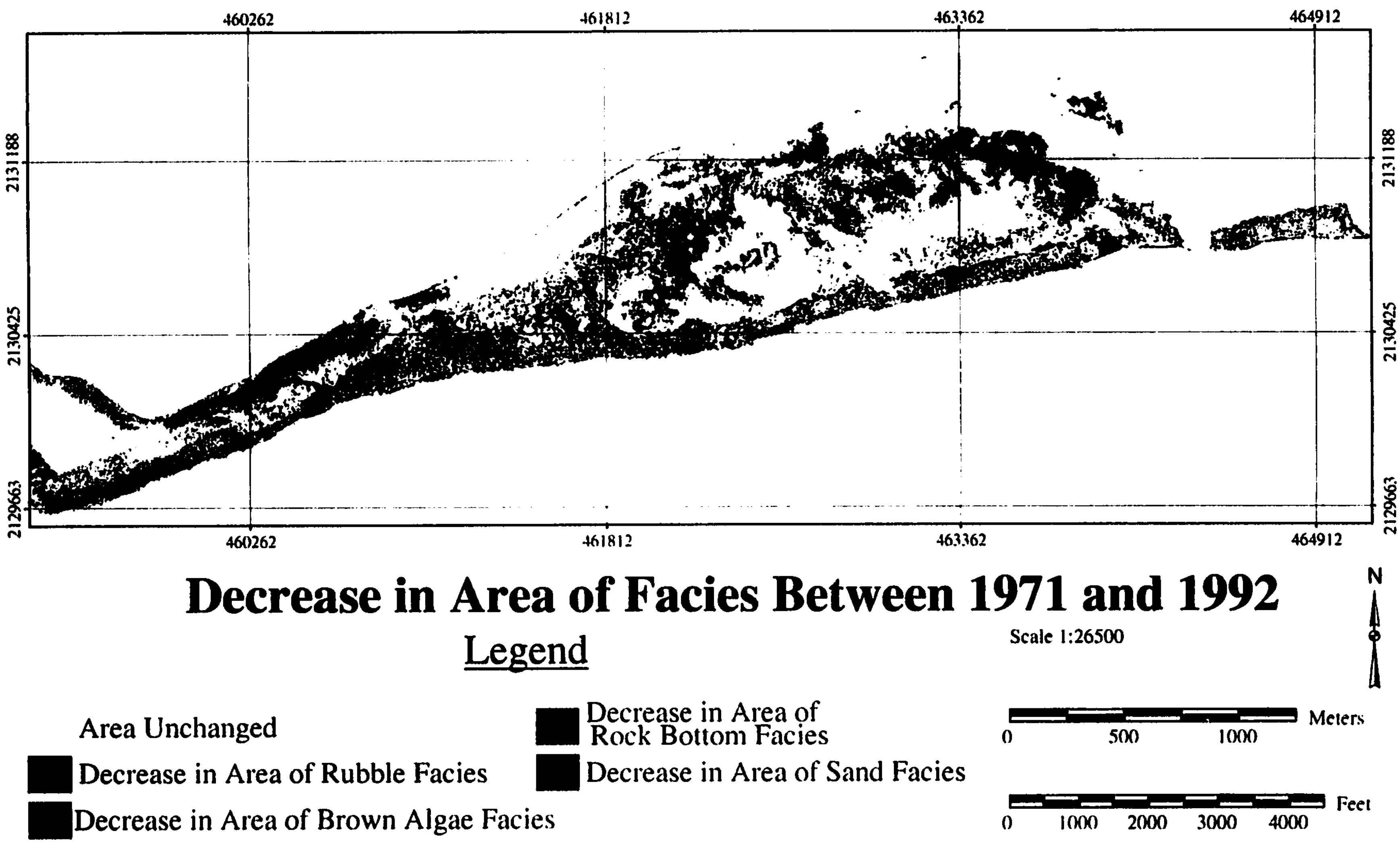

Figure 4.7. South Sound facies having a significant decrease in aerial extent between 1971 and 1992.

studies. Tongpenyai (1989) and Tongpenyai and Jones (1991) discovered that over the 15 year period from 1971 to 1985, *Thalassia* in South Sound expanded by 13%, at the expense of sand. They concluded that most *Thalassia* growth was in the northeastern portion of the lagoon, along the loose sand boundary. They also reported a decrease of *Thalassia* in the western outlet (Roberts *et al.* 1975). Kalbfleisch (1995) and Kalbfleisch and Jones (1998) found that in Pease Bay, which is also on the south shore of Grand Cayman (Fig. 1.2), *Thalassia* also increased at the expense of sand. Between 1985 and 1992, a 5.0% increase occurred in Pease Bay.

The only other facies besides *Thalassia* which increased in area between 1971 and 1992 in South Sound is the Coral Head Facies (+5.8%) (Table 4.1). This increase was concentrated in or very close to the Rubble Facies (Fig. 4.5). The Rubble Facies itself decreased by 2.8% (119, 427 m^2), some of which was in John Bodden Bay (Fig. 4.7). The Rock Bottom Facies also decreased slightly in the west end of South Sound due to the increase of *Thalassia* along the shore, and coral heads near the reef (Fig. 4.7).

4.6 SUBSTRATE FRAGMENTATION IN SOUTH SOUND BETWEEN 1971 AND 1992

Facies patches in South Sound were analysed at the class level, and any patch over 20 m^2 was considered. Overall, the number of patches per class increased between 1971 and 1992, as did the patch density (Table 4.2). This indicates a higher substrate fragmentation level and increasing heterogeneity in South Sound over time.

The facies that expanded the most in South Sound was the *Thalassia* Facies, increasing in area by 17.3% (Table 4.1). *Thalassia* expanded seaward from existing patches or banks, and many new *Thalassia* patches developed (Table 4.2).

Table 4.2. South Sound class-level fragmentation statistics for 1971 and 1992.

Facies	Number of Patches		Patch Density (#/100 ha)		Mean Patch Size (ha)		Patch Size Standard Deviation (ha)		Patch Size Coefficient of Variance (%)	
	1971	1992	1971	1992	1971	1992	1971	1992	1971	1992
Very DenseThalassia	135	289	35.87	83.15	0.01	0.03	0.01	0.16	250.00	607.41
Dense Thalassia	1275	1653	338.77	475.59	0.03	0.03	0.74	0.82	2387.10	2414.71
Medium Thalassia	2581	2651	685.78	752.37	0.01	0.02	0.15	0.36	1161.54	1636.36
Sparse Thalassia	2851	3021	757.52	869.18	0.02	0.02	0.41	0.42	2562.50	2344.44
Rubble	1009	3264	268.09	940.00	0.05	0.01	0.80	0.16	1664.58	1445.46
Coral Heads	486	3016	129.13	867.74	0.01	0.01	0.12	0.07	300.00	1042.86
Brown Algae	3	32	0.80	9.21	2.78	0.19	4.81	1.03	173.07	556.22
Sparsely Vege. Sand	4581	3259	1217.18	937.66	0.01	0.01	0.12	0.09	1344.44	1125.00
Bare Sand	3476	2587	923.58	744.32	0.03	0.02	1.06	0.44	4092.31	2725.00
Rock Bottom	809	1664	214.95	487.76	0.06	0.02	1.45	0.62	2493.10	2836.36

The number of patches for the Very Dense *Thalassia* Facies more than doubles (135 in 1971 to 289 in 1992), and the number of patches for Dense, Medium, and Sparse *Thalassia* Facies also significantly increases. Patch density reflects this increasing fragmentation trend because the area of South Sound in 1971 and 1992 has not changed. It is interesting to note that as the fragmentation index increases, so does mean patch size (Table 4.2). This indicates that existing patches may have grown larger at the same time as new patches were forming. The patch size coefficient of variance is very high when the fragmentation index is very high, indicating that more patches are developing but they are much more variable in size. In 1992, the Sparse *Thalassia* Facies has the greatest patch density even though the Medium *Thalassia* Facies covers the largest area.

The Sand Facies decreased in area by 17.1% between 1971 and 1992 (Table 4.1). This corresponded with a decrease in the number of patches (from 8057 in 1971 to 5846 in 1992) and a significant decrease in patch density. It is evident that many of the sand patches were completely or partially grown over by *Thalassia* because mean patch size and variation in patch size also decreased. The Sparsely Vegetated Sand Facies, which fringes the Bare Sand Facies in the landward direction, had the most overgrowth (29% versus the Bare Sand Facies at 26%).

The Rubble Facies, and especially colonies of coral in and near the Rubble Facies, became much more fragmented since 1971 (Table 4.2). This is primarily due to the fact that there are many more coral head colonies breaking up the rubble zone. The mean coral head colony size increased from 40 m^2 in 1971 to 70 m^2 in 1992, indicating the continued growth rather than retreat of patch reefs. The variability in the size of the patch reefs (patch size coefficient of variance) has increased by 3.5 times.

Both the Rock Bottom Facies and Brown Algae Facies became more fragmented during this 21 year period. The mean patch size of the Rock Bottom Facies was 0.06 ha in 1971, with the patch size varying by 1.45 ha; in 1992 the mean patch size decreased to 0.02 ha, and the patch size standard deviation also decreased to 0.62 ha. Therefore, the Rock Bottom Facies broke up into more and smaller patches. Similarly, the Brown Algae Facies was broken up into smaller patches.

4.7 SYNOPSIS

The distribution of facies in South Sound changes systematically from shoreline to reef crest: Very Dense *Thalassia* Facies, Dense *Thalassia* Facies, Medium *Thalassia* Facies, Sparse *Thalassia* Facies, Sparsely Vegetated Sand Facies, Bare Sand Facies, Coral Head Facies, and Rubble Facies, with the Rock Bottom and Brown Algae Facies disrupting this pattern in the far west and far east of the lagoon, respectively.

Facies changes throughout the length of the core indicate that the lagoonal system is a dynamic one. Core SSC5 and SSC6 contain the Dense *Thalassia* Facies, even though they were obtained in the Bare Sand Facies and Medium *Thalassia* Facies, respectively.

Digital image analysis of South Sound in 1971 and 1992 confirm that there were changes in the distribution, aerial extent, patch size, and patch density of each facies. The major change in facies over this 21 year period was an increase in the area of the

Thalassia Facies by 17.3%, predominantly at the expense of sand, which decreased by 17.1%. The *Thalassia* Facies did not only increase from existing patches and banks, but new patches have also been initiated. The Coral Head Facies increased by 5.8%, indicating that patch reef development is still in the constructive phase.

CHAPTER 5

EVOLUTION OF FACIES DISTRIBUTION IN SOUTH SOUND

Sediment deposition patterns in a shallow lagoon are a function of sediment production and sediment dispersal. The former is controlled by the distribution of plants and animals, and by mechanical abrasion of the reef crest by waves during storms. The latter is controlled by normal everyday waves and currents, and by more intense waves and currents generated by episodic storms. Sedimentological, textural, compositional, and biotic characteristics of most of the facies in South Sound indicate that currents and waves have modified the *in situ*, fair-weather sediments. Only the Rubble Facies is produced and distributed solely by higher energy storms.

Fair-weather processes dominate *in situ* sediment production, with minor post-depositional modification (Fig. 5.1). All lagoons are influenced to some extent by fair-weather processes, so many studies have focussed on carbonate sediment production by plants and animals, and quiet-water skeletal breakdown (e.g. Swinchatt 1965; Maiklem 1968; Aller and Dodge 1974; Wefer 1980; Hudson 1985; Bak 1994; Harney *et al.* 1999). The most common sediment producers are mollusks, green algae, foraminifera, and *Thalassia* epibionts. Carbonate sediment is produced as biota die and disintegrate. Sorby's (1879) principle demonstrates that each plant or animal will first break along its structural boundaries, and then along its crystallographic boundaries (Folk and Robles 1964). This produces a sediment that has a polymodal distribution, with each grain size fraction corresponding to a unique biotic type. Sorting and skewness will vary with the local biotic community (Swinchatt 1965).

Under fair-weather conditions, lagoons characteristically have low water energy. Sediment reworking is minimal because of the low energy waves and currents. Bioturbation and micritization are extensive, and fragmentation and mechanical abrasion are low. *Thalassia* colonization under low energy conditions is uninhibited where there is a sufficient thickness of sediment to allow the plants to root themselves.

Local sediment production under quiet-water conditions is a daily occurrence in South Sound (Fig. 5.1). Each *Thalassia* plant supports a multitude of epibionts, which forms a thin film on the blades. When the grass blades fall, this heavy encrustation disintegrates to produce a fine calcite mud (Stockman *et al.* 1967; Nelsen and Ginsburg 1986). The binding of the substrate by *Thalassia* roots prevents erosion (Neumann *et al.* 1970), and the baffling by the blades encourages sediment settling from suspension (Almasi *et al.* 1987). This causes the grass-covered areas of South Sound to be raised into banks due to the preferential accumulation of sediments in those areas. Algal and biotic breakdown are also common in South Sound. Mollusk and *Halimeda* fragments are the most abundant components of the sediment grains, accounting for at least 65% of the total sediment. Living mollusks and *Halimeda* are common within the confines of the lagoon. Hillis-Colinvaux (1980), Wefer (1980), Hudson (1985), Multer (1988), and Nittrouer and Bentley (1997) estimated that the amount of sediment produced by *Halimeda* in a tropical environment is between 50 $g/m^2/year$ - 1088 $g/m^2/year$. Mollusks contribute to the carbonate sediment as they die and break apart.

The sediments in South Sound have been influenced by high energy processes. The grain size of the sediments varies with the position in the lagoon. Fine-grained sediments in the northeast corner contrast with the coarse-grained sediments near the reef crest and in the west outlet channel. The sediments in all facies except the Rubble Facies are unimodal and moderately sorted, and do not reflect the structural size of the local biotic community. Fragmentation and abrasion of the grains is common. These characteristics of the sediments in South Sound imply that there was extensive sediment reworking following deposition.

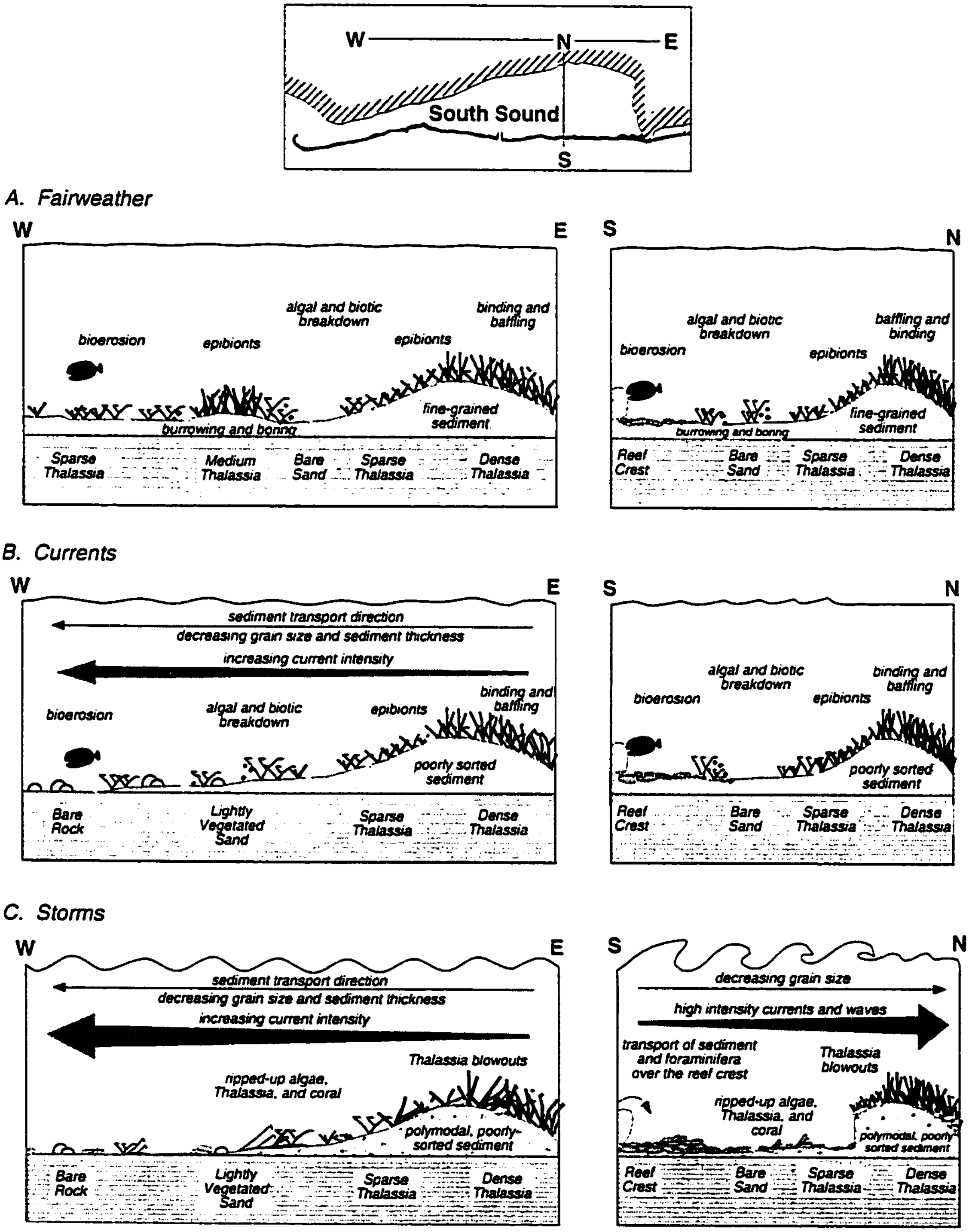

Figure 5.1. Model of the processes in South Sound and John Bodden Bay. These lagoons have evolved as a result of all three processes acting together.

When the conditions affecting Grand Cayman are not completely calm, everyday currents are generated along the axial plane of South Sound. Currents in a lagoon can be generated by density gradients, winds, and tides. The everyday currents in South Sound develop primarily as a response to wind-generated waves breaking over the length of the reef crest, with some tidal influence. South Sound is located on the exposed windward south coast of Grand Cayman, where the effects of wind are considerable. The dominant winds affecting Grand Cayman are the northeast trade winds, which have average speeds of 5 - 7 m/sec, and almost always have an easterly component (Roberts *et al.* 1975). These winds induce waves in the deep water almost daily, and the generated waves approach South Sound from the south-southeast. They are not refracted around the island because the shelf surrounding Grand Cayman is too narrow. Instead, they are produced by the lower strength south-southeast component of the northeast winds. Components of the wind will spread 90° from the dominant wind direction (Roberts *et al.* 1975). Winds may blow from the northwest or west during winter storms, although this happens much less frequently. During these periods, however, South Sound is sheltered from the wind and waves, and it becomes a safe place for boats to be anchored. The waves approaching South Sound have a height and period that are moderate to low (< 1 m and 6 seconds, respectively) but vary with water depth, wind velocity, duration, and fetch length (Von Arx 1948; Roberts 1974).

As waves pass over the reef crest of South Sound, they are significantly modified, and this induces circulation in the lagoon. Due to the shallow depth of the reef crest, the deep water waves break over it, significantly depreciating both in wave height and energy (Roberts *et al.* 1975). The velocity with which water enters the lagoon is modified by the tides, even though the tidal range of Grand Cayman is small, averaging 35 cm. At low tide, there will be less water over the reef, so wave-breaking and set-up will be enhanced (Suhayda and Roberts 1977; Roberts 1980). This increases the force with which water enters the backreef area. The water influx into South Sound takes the form of surge currents, which enter the lagoon at a slight angle to the shoreline. These currents have an average speed of 10 cm/sec (Roberts *et al.* 1975; Suhayda and Roberts 1977). South Sound is a narrow, trade wind-parallel lagoon, so the circulation is westerly for 95% of the time (Darbyshire *et al.* 1976). Currents in the east end of the lagoon are only 6 cm/sec, but they gradually accelerate towards the west as Pull-and-be-damned Point is approached because the water is funneled through the continuously narrowing lagoon. It is difficult to swim in the western outlet without boat support, due to the strength of the currents. The currents reach a maximum speed of 45 cm/sec at the narrowest part of the lagoon, and then begin to slow again where the lagoon widens out beyond the reef crest (Roberts *et al.* 1975; Darbyshire *et al.* 1976; Suhayda and Roberts 1977). The normal current speed for wave-dominated lagoons affected by the northeast trade winds is 10 - 20 cm/sec (Roberts 1988).

The distribution, composition, and texture of the sediments in South Sound show evidence that this lagoon is current-dominated. The sediments are thickest where the currents are the weakest, and gradually thin as the current speed increases (Fig. 5.1). Maximum sediment accumulation is in the east part of the lagoon, where sediments are up to120 cm thick (Fig. 4.2). In the central part of South Sound, the sediments are 25 - 50 cm thick, and there are only a few centimetres of sediment covering the rocky substrate in the narrow western outlet. The area of South Sound that is least affected by the currents is the sheltered northeast corner, where sediments are rich in organics that come from the surrounding mangroves. This is the location of the finest-grained sediments, consisting primarily of fine sand to clay-sized sediment. In central South Sound, the sediments are predominantly medium sand-sized. Large unidirectional current ripples that are parallel to the direction of waves entering the lagoon (south south-east) are present in the Bare Sand Facies near the reef crest. These ripples have a transverse sinuous shape, and traction of sand-sized grains up the stoss side of the ripple to the crest was apparent under normal current conditions. Currents that are 40 - 60 cm/sec are able to move sand grains of 1 - 2 mm in size by bedload transport. Currents of 45 cm/sec in the western part of South Sound effectively transport most of the sand-sized sediment from the area, except for where there are small pockets in the bedrock. This sediment is carried out of the lagoon and is deposited on the southwestern shelf as the currents decelerate (Murray *et al.* 1977; Roberts and Snieder 1982; Roberts 1983). Coarse sand-sized sediments are dominant in the outlet channel, where the water is deepest and fastest.

The varying energy levels produced by the wave-induced currents in South Sound and John Bodden Bay are reflected in the patterns and the systematic distribution of the facies. The Brown Algae Facies in the northeast corner of South Sound is sheltered from currents, because the currents enter the lagoon from the south south-east. These almost stagnant waters allow fine sediments to settle from suspension, and thick muddy accumulations are produced. The Very Dense and Dense *Thalassia* Facies are situated in long, narrow bands that parallel the shoreline, where current energy is low (Fig. 3.1). Fine-grained sediment settles out of the water due to the baffling action of the blades, but sediment thickness depends on sediment supply. Most of the sediment has been trapped in the Dense *Thalassia* Facies before it reaches the more shoreward Very Dense *Thalassia* Facies. The areas with sparse *Thalassia* growth are in the central part of the lagoon, where the current speeds are moderate. Less sediment accumulates where the *Thalassia* cover is sparse because current speed reduction by the blades is not as efficient. Consequently, sediments are thin, which results in thinner and shorter *Thalassia* plants. The Bare Sand Facies and Rubble Facies, which are situated just behind the reef crest, are also affected by moderate strength currents. The currents enter the lagoon from the south-southeast, so sediment migration in the Rubble Facies and Bare Sand Facies is to the north-northwest (Fig.

3.1). The east to west current movement in the eastern part of the lagoon and just behind the reef crest is poorly developed. The west-flowing currents become stronger as the lagoon narrows in the west, where the Rock Bottom Facies is stripped of loose sediment.

Lagoons dominated by fair-weather processes commonly have low biotic diversities, but many species are well established in South Sound and John Bodden Bay. The most robust biota such as corals, brown algae, and some green and red algae grow in the highest energy Rubble Facies and Rock Bottom Facies (Fig. 5.1). The brown algae species including *Dictyota* sp. *Stypopdium zonale, Turbinaria* sp., and *Padina* sp., grow in exposed areas with moderate to strong water movement. The less robust biota, such as *Thalassia,* are limited to growth in areas sheltered from strong currents.

Everyday waves and currents are augmented by the unusually strong waves and currents that are produced by storms and hurricanes. Storm currents in South Sound travel in the same direction as everyday currents, but the increase in magnitude causes the processes to be exaggerated.

Grand Cayman is regularly affected by storms and hurricanes; hurricanes cross over the island with a recurrence interval of about 10 (Clark 1988; Burton 1994) to 20 years (Blanchon 1995). The wind direction during a hurricane changes as the eye passes over the island, but many hurricanes in the past have had a direct impact on the south coast (Hirst 1910). The main processes that take place during hurricanes are increased wave height and intensity; the piling up of water against the shore during the hurricane approach; and the release of this water as rip currents as the storms wanes (Kalbfleisch 1995; Kalbfleisch and Jones 1998). With the increase in wave height and intensity, waves breaking over the reef crest become more violent and currents entering the lagoon increase substantially in strength. The circulation pattern of South Sound will be temporarily modified. Water will continue to drain from east to west, but a strong current flowing north towards the shoreline will develop (Fig. 5.1).

Storms and hurricanes are infrequent but intense events that have a major impact on the sediment and facies distribution in a lagoon. Storm energy is the most concentrated and most vigorous at the reef crest, so this is where most storm sediment production takes place. The main effect of storms is to distribute coral fragments from the reef into the Rubble Facies belt, which is present in both John Bodden Bay and South Sound (Fig. 3.1). The cobbles in the Rubble Facies are predominantly composed of *Acropora palmata*, a branching coral. *Acropora palmata* inherently breaks into long fragments with varying branch thicknesses. The thickest branches in the Rubble Facies are 16 cm in diameter. Intense waves and currents are necessary to break 16 cm thick branches, but the actual force required depends on the degree of boring (Hernandez-Avila *et al.* 1977). The coral rubble averages 20 - 30 cm in length, and storm waves and currents are able to transport it a distance of up to 250 m into the lagoon (maximum extent of the Rubble Facies in South Sound). John Bodden Bay is < 250 m wide; thus, the storms can distribute the coral rubble north across the lagoon and onto the shore. The coral rubble along the shoreline of John Bodden Bay is up to 50 cm x 25 cm.

The backreef Rubble Facies in South Sound stretches along the length of the reef crest (Fig. 3.1), but coral rubble is not confined to this facies. Smaller quantities of rubble can be found along the shoreline and scattered throughout the entire lagoon. The cobbles found along the shoreline in South Sound are smaller then those found along the shoreline in John Bodden Bay, having a maximum size of 24 cm x 12 cm. The largest cobbles are deposited directly behind the reef crest, and gradually decrease in size towards shore, as the currents are attenuated. Storm currents act for a very short time, so the largest coral pieces cannot be transported far from the reef (Ball *et al.* 1967). Erratic coral fragments can be found throughout South Sound, even where currents are slowest such as in the sheltered Brown Algae Facies.

The transport of sand into, within, and out of South Sound is greatly enhanced during a storm. Sediment transport into the lagoon takes place as high-intensity waves carrying sediment wash over the reef crest (Fig. 5.1). Sediment sources can be traced by studying foraminifera. Benthic foraminifera in the backreef and up to 500 m into the lagoon are composed of a mixture of both lagoonal and forereef taxa (Li 1997). These forereef taxa were transported over the reef crest during storms or hurricanes (Li 1997). Sediment transport within South Sound is common. The sand lobes of the Bare Sand Facies migrate shoreward at an accelerated rate during storms. As the current speed increases to the west, higher quantities of sediment are transported. The Rock Bottom Facies, which floors the west outlet channel, acts as a corridor for the transport of sediment onto the shelf edge. Hubbard (1992) studied the hurricane processes in a modern lagoon on St. Croix and found that the transport rate of sediments during hurricanes was increased by eleven times over fair-weather conditions.

Storms can have a devastating effect on the biota in a lagoon. Large blowouts in the *Thalassia* in South Sound and John Bodden Bay are evidence of this (Fig. 3.3A). These grass-free areas require currents that are much stronger than those produced under normal current conditions (Neumann *et al.* 1970; Scoffin 1970). Live individual corals and coral colonies can be ripped-up and destroyed during storms. Unattached and mangled gorgonians are common in South Sound.

Together, the fair-weather, current, and storm processes produce a constantly changing lagoonal environment. Of the facies changes that took place in South Sound and John Bodden Bay between 1971 and 1992, the most significant was the increase in the *Thalassia* Facies. During that period, *Thalassia* increased in area at a rate of ~57, 700 m^2/year. If it continues to expand at this rate, the entire lagoon will be covered in approximately 60 years. Areas that are covered by *Thalassia* become shallower due to the sediment accumulation by binding and baffling of the plants. This will reduce current speed and eventually change the circulation patterns in the lagoon. As the processes and sedimentology change, the biota will also change. More *Thalassia* plants will be able to take root as the surrounding sediment thickens. The entire coverage of South Sound and John Bodden Bay by *Thalassia*, however, has not happened, because of a limiting force. Although *Thalassia* is a fairly tolerant and versatile plant, it will not survive in areas of strong currents, as evidenced by blowouts. Defoliation of *Thalassia* plants will not take place until currents in sparse *Thalassia* reach 50 cm/sec, and in dense *Thalassia* reach 150 cm/sec (Scoffin 1970). Therefore, the blowouts in South Sound must have been eroded during the intermittent strong currents and waves produced by storms. Once the *Thalassia* plants were defoliated by storms, the sparse *Thalassia* coverage was maintained by everyday currents. Where the currents are strongest, such as over the Rock Bottom Facies, there is minimal sediment accumulation, and *Thalassia* plants cannot take root. *Thalassia* expansion will continue to be limited in areas where currents remain strong.

The significant increase in the area of *Thalassia* between 1971 and 1992 can be attributed to several factors. A mass mortality of the sea urchin, *Diadema antillarum*, took place in Caribbean waters in 1983 (Bak 1977; Carpenter 1985, 1988; Hughes *et al.* 1985; Hunte *et al.*, 1986). *Thalassia* is a major food source for *Diadema antillarum*, whose feeding habits produce grass-free halos around patch reefs and reefs (Ogden and Zieman 1977). Hartog (1977) suggested that there is a succession in lagoonal communities, with bare sand being progressively overgrown, until it eventually hosts a *Thalassia* community. The 17.3% increase in the area of *Thalassia* and the 17.1% decrease in the area of sand in South Sound between 1971 and 1992 is probably evidence of this process.

The biotic and abiotic systems in South Sound are continually striving toward equilibrium as lagoonal dynamics are changing. If the facies continue to shift and break up as they had between 1971 and 1992, South Sound will become increasingly heterogeneous. The high facies fragmentation will cause current speeds and paths to become interrupted by the varying substrate patches. This gradual change in energy circulation will eventually be reflected in the distribution and composition of materials and species communities. For example, patch density and mean patch size show that *Thalassia* increased by the expansion of current patches, as well as by the creation of new patches (Table 4.2). New patches are forming in the Sparsely Vegetated Sand Facies in close proximity to existing *Thalassia* patches. These areas may be in bedrock depressions, where the accumulating sediment influenced by the surrounding *Thalassia* blades may reach thicknesses allowing increased stability for *Thalassia* growth. *Thalassia* growing where the Sparsely Vegetated Sand Facies is will change the niche and the species of both plants and animals that can be supported.

Modern sedimentological evidence from South Sound indicates that the recognition of ancient lagoonal deposits can be complicated if a lagoon is dominated by higher energy processes. Lagoons are typically considered to be quiet-water environments with abundant fine-grained sediments that settle from suspension (Tucker and Wright 1990; Davis 1983; Boggs 1995). Consequently, sessile organisms should be deterred from inhabiting lagoons (Boggs 1995). The reef surrounding a lagoon is thought to protect it from the waves, currents, and tidal fluxes which disturb the sediments beyond the reef crest (Tucker and Wright 1990; Davis 1983; Boggs 1995). Coarser-grained sediments influenced by higher energy processes within the lagoon are considered to be rare, and are found only if tidal channels develop inside the lagoon, or if storms wash in forereef sediments (Boggs 1995). Therefore, in ancient successions, quiet-water, fine-grained autochthonous deposits with low faunal diversities and extensive bioturbation are commonly inferred to be lagoonal deposits.

This study and other studies of modern lagoons (Von Arx 1948; Maxwell *et al.* 1961; Ball *et al.* 1967; Suhayda and Roberts 1977; Roberts 1983; Hubbard 1992; Kalbfleisch 1995; Kalbfleisch and Jones 1998; Kench 1998) indicate that higher energy currents and storms may dominate the textures and composition of the sediments in a lagoon. Unimodal, moderately-well sorted sand-sized deposits may indicate that the lagoon was dominated by currents, and abundant polymodal, cobble- to boulder-sized coral rubble may indicate a storm-dominated lagoon. Lagoon sedimentation will not always reflect quiet-water conditions.

CONCLUSIONS

The sedimentology of South Sound and John Bodden Bay are controlled by the interplay of fair-weather, current, and storm processes. Specifically:

- fair-weather processes are dominated by sediment production, bioerosion, bioturbation, and uninhibited *Thalassia* colonization,
- under fair-weather conditions baffling and binding by *Thalassia* promotes thick sediment accumulations,
- current processes are dominant in South Sound, because they influence the composition and texture of the sediments post-depositionally, erasing most of the evidence of fair-weather processes,
- the position, orientation, and geometry of South Sound contributes to the amplification of the trade wind-generated axial currents, which sort, fragment, and redistribute sediments,
- the currents intensify from east to west in South Sound, causing the sediments to thin and the grain size to increase in this direction,
- the facies distribution reflects the local current energy, with the most robust biota growing in the west and close to the reef, where currents are strongest,
- storms enhance the effects of everyday currents, distributing a decreasing grain size and concentration of coral rubble across the width of the lagoon,

All three processes acting in South Sound result in a lagoon that is constantly striving toward a dynamic equilibrium.

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APPENDIX A

1 M X 1 M GRID COUNTS

Number of species of each biota type for 1 m x 1 m grids in various facies of South Sound.

	Grid 1 Dense Thalassia	*Grid 2 Rubble*	*Grid 3 Brown Algae*	*Grid 4 Rock Bottom*	*Grid 5 Rubble*	*Grid 6 Dense Thalassia*	*Grid 7 Dense Thalassia*	*Grid 8 Bare Sand*	*Grid 9 MediumThalassia*	*Grid 10 Bare Sand*	*Grid 11 Sparse Thalassia*	*Grid 12 Rubble*	*Grid 13 Sparse Thalassia*	*Grid 14 Rock Bottom*
Thalassia testudinum	1064	0	0	56	0	1776	1324	6	448	0	0	250	248	0
Syringodium filiforme	0	0	0	0	0	0	0	0	0	27	0	0	0	0
Penicillus sp.	0	0	7	58	4	0	20	0	0	0	0	0	0	13
Halimeda sp.	24	0	37	16	9	0	19	10	0	2	0	2	5	0
Acetabularia crenulata	0	0	0	5	0	0	85	0	0	1	0	0	0	51
Dasycladusvericularis	0	0	0	76	0	0	4	0	0	0	0	0	0	0
Dictyota sp.	0	0	0	0	15	0	0	0	0	1	14	0	0	0
Padina jamaicensis	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Caulerpa mexicana	0	0	0	0	0	0	15	0	0	0	0	0	0	0
Caulerpa cupressoides	0	0	0	0	0	0	28	0	0	0	0	0	0	0
Udotea sp.	0	0	0	0	2	0	0	0	0	0	7	0	0	0
Jarnia adherens	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Callanassa	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Valonia macrophysa	4	0	0	4	0	0	1	0	0	0	0	0	0	0
Microdictyon boergesenii	no	no	no	no	no	no	no	no	no	no	yes	no	no	no
Rhodolites	0	5	0	40	0	1	0	0	0	0	0	0	0	0
Bispira variegata	0	0	0	2	0	0	0	0	0	0	0	0	0	0

APPENDIX B
GRAIN SIZE ANALYSIS STATISTICS

Data determined from histograms and cumulative probability plots.

Thalassia **Facies**

Sample Number	*Mode Ø*	*Mean Ø*	*Sorting Ø*	*Skewness*
Very Dense Thalassia				
A1	*3.50*	*2.30*	*1.69*	*-0.09*
Dense Thalassia				
A2	*1.00*	*0.96*	*1.51*	*0.13*
A8	*2.00*	*1.85*	*0.90*	*0.03*
C1	*1.00*	*1.01*	*0.95*	*0.05*
E1	*1.00*	*0.95*	*0.85*	*0.07*
G1	*1.00*	*1.03*	*1.38*	*-0.04*
Medium Thalassia				
A4	*1.75*	*1.63*	*1.30*	*0.08*
A10	*2.00*	*1.60*	*0.75*	*0.03*
C2	*2.00*	*1.40*	*1.43*	*0.02*
C12	*3.00*	*2.19*	*1.24*	*-0.14*
C14	*3.00*	*2.41*	*1.38*	*-0.12*
D1	*1.00*	*0.95*	*1.04*	*0.15*
F8	*1.00*	*0.46*	*0.42*	*0.03*
G2	*1.00*	*1.22*	*1.25*	*0.05*
G4	*3.00*	*1.58*	*1.14*	*0.01*
Sparse Thalassia				
A12	*1.00*	*1.36*	*1.09*	*0.09*
C8	*3.00*	*1.88*	*1.19*	*-0.03*
C10	*1.00*	*1.56*	*1.41*	*0.16*
D3	*1.00*	*0.55*	*0.82*	*0.00*
G6	*1.00*	*1.28*	*1.10*	*0.07*
G7	*0.50*	*0.72*	*1.05*	*0.08*
G8	*2.75*	*1.63*	*1.33*	*-0.03*
G10	*0.50*	*0.78*	*1.17*	*0.17*

Sand Facies

Sample Number	*Mode Ø*	*Mean Ø*	*Sorting Ø*	*Skewness*
A6	*2.00*	*2.08*	*1.03*	*-0.02*
A14	*2.75*	*2.18*	*0.87*	*-0.16*
A15	*2.75*	*1.86*	*1.11*	*-0.18*
A16	*2.00*	*1.38*	*1.15*	*-0.09*
A18	*2.00*	*1.51*	*1.23*	*-0.08*
B3	*2.00*	*1.55*	*0.96*	*-0.11*
C4	*3.00*	*1.82*	*1.05*	*-0.10*
C6	*3.00*	*1.82*	*0.99*	*-0.05*
C16	*1.51*	*1.62*	*1.10*	*0.06*
M3	*3.00*	*2.09*	*0.79*	*-0.20*

APPENDIX B (CONTINUED)

Brown Algae Facies

Sample Number	Mode Ø	Mean Ø	Sorting Ø	Skewness
M1	0.50 & 2.00	0.93	1.31	0.15
SSC8	<4.00 & 1.00	1.88	1.72	-0.02
SSC9	<4.00 & 2.00	2.93	1.34	-0.05

Rubble Facies

Sample Number	Mode Ø	Mean Ø	Sorting Ø	Skewness
A20	1.00	0.75	0.74	0.01
B1	1.00	0.73	1.18	0.07
B2	1.00	0.85	0.92	-0.07
C18	>-1.00	-0.26	1.40	-0.04
D4	0.00	0.10	0.70	0.05
D5	0.50	0.27	0.55	-0.10
G11	2.00	1.11	1.38	-0.17
H1	0.75	1.46	0.52	-0.27
Backreef #1	-7.50	-5.98	0.86	-0.01
Midreef #1	-7.00	-7.02	0.69	-0.06
Reefcrest #1	-8.00	-6.90	0.70	0.09
Backreef #2	-6.50	-6.38	0.79	-0.03
Midreef #2	-7.00	-7.12	0.50	-0.06
Reefcrest #2	-7.50	-7.30	0.82	-0.21

Rock Bottom Facies

Sample Number	Mode Ø	Mean Ø	Sorting Ø	Skewness
B5	0.50	0.44	0.63	0.07
E2	1.00	0.57	1.45	0.01
E4	1.00	0.82	1.11	-0.09
F3	0.50	0.07	1.20	-0.19
F4	0.00	-0.03	0.96	0.06
F5	0.50	0.38	0.72	0.05
F6	1.50	0.78	0.67	-0.05

Beach

Sample Number	Mode Ø	Mean Ø	Sorting Ø	Skewness
F2	1.00	0.58	0.70	-0.04