Dynamic Carbonate Sedimentation in a Shallow Coastal Lagoon: Case Study of South Sound, Grand Cayman, British West Indies

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ABSTRACT

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South Sound is a 3.4 km^2, shallow ($<$ 2 m), funnel-shaped lagoon located on the southwest exposed windward margin of Grand Cayman. The composition and distribution of the *Thalassia*, Sand, Rock Bottom, Brown Algae, Rubble, and Coral Head facies, are controlled by the dynamic interplay between fair-weather conditions and storms. Under fair-weather, quiet-water conditions, sediment production, bioturbation, and expansion of the *Thalassia* banks are the dominant processes. The combination of the onshore northeast trade winds and funnelling caused by the shape of the lagoon, however, produce currents that strengthen 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 sparse and coarse-grained in the west. Hurricanes directly impact the reef crest and produce coral fragments (dominantly *Acropora palmata*) that are concentrated in the rubble facies landward of the reef. Strong onshore and westward flowing currents induced by the storms and hurricanes extensively rework and redistribute the sediments in the lagoon. As a result, the sediments and facies distribution are primarily a reflection of the short-lived, aperiodic storm events rather than the fair-weather processes.

ADDITIONAL INDEX WORDS: *Thalassia*, reef, storm, fair-weather, facies, coastal processes, substrate, grain size analysis, coral, carbonate sediment.

INTRODUCTION

Lagoons are typically considered to be peaceful environments where diverse biota thrive and fine-grained sediments accumulate (*e.g.*, TUCKER and WRIGHT, 1990; DAVIS, 1983; BOGGS, 1995). Such tranquility is typically due to an offshore reef that acts as a barrier against onshore waves, currents, and tidal fluxes (*e.g.*, TUCKER and WRIGHT, 1990; DAVIS, 1983; BOGGS, 1995). Lagoons characterized by coarse-grained sediments that formed under the influence of high energy processes are considered to be rare, and restricted to those settings where tidal channels develop, or where storms wash in forereef sediments (*e.g.*, BOGGS, 1995). Other studies of modern lagoons, however, have shown that higher energy conditions are responsible for the composition and distribution of sediments in a lagoon (*e.g.*, VON ARX, 1948; MAXWELL *et al.*, 1961; BALL *et al.*, 1967; SUHAYDA and ROBERTS, 1977, 1983; HUBBARD, 1992; KALBFLEISCH, 1995; KALBFLEISCH and JONES, 1998; KENCH, 1998). In most cases, development of these sediments is attributed to short lived, storm-induced high energy conditions.

South Sound is a small, shallow lagoon situated on the south coast of Grand Cayman (Figure 1A, B). Sedimentation in South Sound is a product of the interaction between fair-weather and storm processes. The sediments and facies distribution, however, are primarily a reflection of currents, and especially storm generated currents. The wave, wind, and current regimes of South Sound have been well established by ROBERTS *et al.* (1975), DARBYSHIRE *et al.* (1976), MURRAY *et al.* (1977), SUHAYDA and ROBERTS (1977), and ROBERTS (1983). Integration of that information with the grain-size, sorting, composition, biotic density and diversity, and facies distribution information obtained during this study allows the development of an integrated sedimentation model for South Sound. As such, it provides an understanding of carbonate sedimentation in a shallow coastal lagoon that is influenced by high-energy processes.

SETTING AND PHYSICAL CONDITIONS

South Sound is 5 km long, 1.1 km wide at the east end, and 275 m wide at the west end, with an area of 3.4 km^2 (Figure 1C, D). It is fringed by land to the north and east, and by a barrier reef to the south. A red mangrove swamp fringes the northeastern margin. South Sound is completely enclosed, except for the west end, where it is open to the Caribbean Sea. A narrow, man-made channel cuts through

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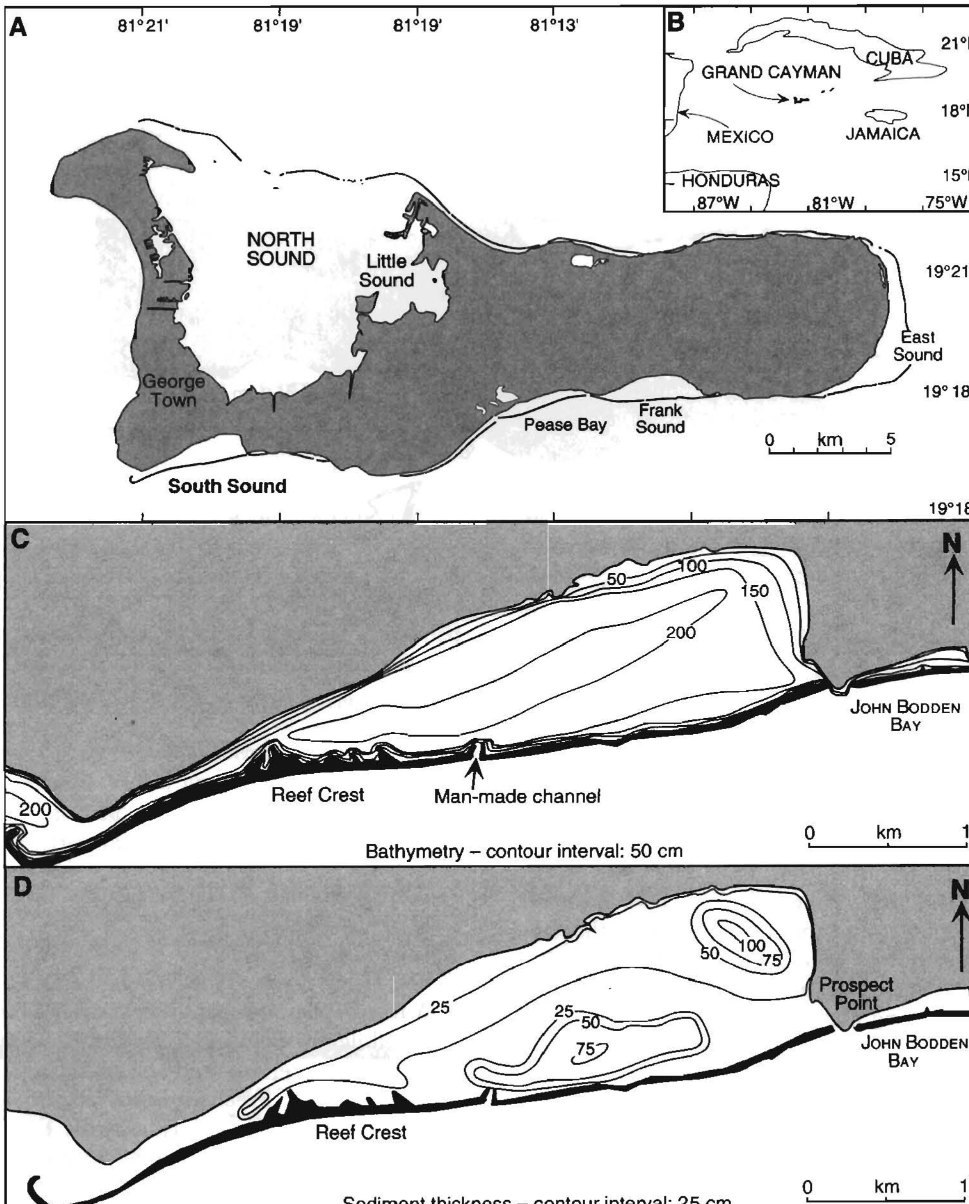

Figure 1. (A) Location of Sound Sound on Grand Cayman. (B) Location of Grand Cayman. (C) Bathymetry of Sound Sound, contour interval of 50 cm. (D) Sediment thickness in South Sound, contour interval of 25 cm.

the reef approximately halfway along its length (Figure 1C). Water discharge from the land into the lagoon is minimal.

Bathymetry and Sediment Thickness

On average, the water in South Sound is 1.65 m deep, with the maximum depth of 2.5 m in the centre of the lagoon (BEANISH, 2000; Figure 1C). From there, the water progressively shallows shoreward and towards the reef crest (Figure 1C). Local changes in bathymetry are related to blowouts, *Thalassia* banks, patch reefs, *Calianassa* mounds, and sediment-free areas.

The average sediment thickness in South Sound is 25 cm (BEANISH, 2000). Small areas with thicker sediment accumulation are scattered throughout the lagoon (Figure 1D).

Climate

Grand Cayman has a sub-humid tropical climate with seasons marked by changes in rainfall. During the summer, the average temperature is 28.4°C. The temperature drops to its average low of 24.8°C in February. Rainfall, which averaged 1513 mm/year between 1920 and 1987, is seasonally and geo-

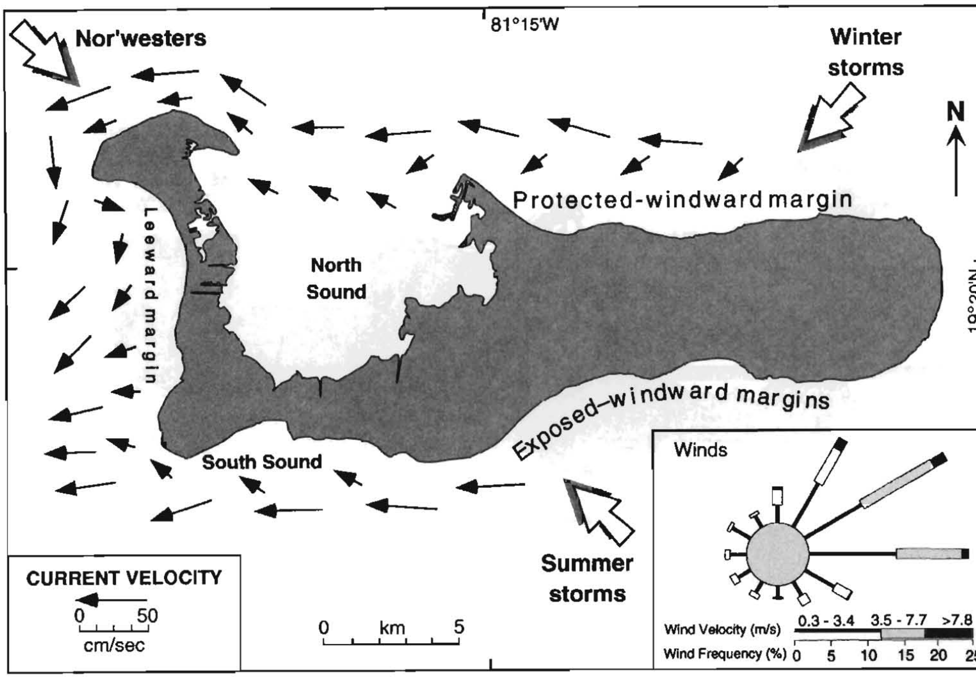

Figure 2. Wind (modified from Darbyshire et al., 1976) and current strengths and directions (modified from Blanchon and Jones, 1995) around Grand Cayman.

graphically variable (RIGBY and ROBERTS, 1976; BESWICK, 1980).

Winds are generally from the east, varying slightly north or south—typical of the Trade Wind Belt (Figure 2). The wind speed decreases in summer and changes direction in the winter. Between November and March, cold fronts emanating from North America briefly bring colder temperatures and storms along with a strong northwesterly wind (Nor'wester Gales). Hurricanes, which generally occur between August and October, pass within 10 km of the island with an average recurrence interval of 10 (CLARK, 1988; BURTON, 1994) to 20 years (BLANCHON, 1995). Hurricanes from the south and southeast have a direct impact on South Sound.

Marine Hydrology

The waters around the island are remarkably clear, and turbidity is low. Salinity is 35–38‰ (BURTON, 1994). The low-amplitude tides (maximum 60 cm, average 35 cm—RIGBY and ROBERTS, 1976) control the open shelf current regime. Waves, which develop in response to the Northeast Trade Wind System, typically approach Grand Cayman from the southeast to northeast. The south and east coasts, which receive the strongest wave energy for most of the year, are the exposed-windward margins (BLANCHON, 1995; BLANCHON and JONES, 1995; BLANCHON *et al.*, 1997) (Figure 2). Waves are rarely more than 1.8 m high with a period of 6 seconds (RIGBY and ROBERTS, 1976).

Marine Geomorphology

The forereef shelf, typically < 1 km wide, is divided into two parts by a mid-shelf scarp (WOODROFFE *et al.*, 1983; ROBERTS, 1974, 1983, 1994; BLANCHON and JONES, 1995). The shelf edge is delineated by a near-vertical wall.

METHODS

Field Methods

Water depth, sediment thickness, sediment samples and detailed descriptions of the substrate, biota, flora and fauna density and diversity, and sedimentary textures were taken along six shore to reef transects (Figure 3). Additional samples were collected at localities B1-B5 (Figure 3). Facies boundaries were constrained by air-photograph analysis and additional ground-truthing. The facies distribution, their aerial extent, and changes in facies over time were determined by digital image analysis (BEANISH, 2000; BEANISH *et al.*, *in press*).

Sediment cores, obtained where sediment thickness was sufficient (Figure 1D), were obtained by hammering a 1.5 inch diameter PVC pipe into the sediment until it hit bedrock. Biota diversity counts are based on surveys of thirteen randomly located 1 m x 1 m grids. For the reef rubble, 50 randomly selected cobbles were measured at various locations in the backreef, midreef, and reef crest area.

Grain Size Analysis

Grain size analysis of 50 loose sediment surface samples and two sediment cores followed FOLK (1968). Most samples contained < 5% clay and silt. Each sample was sieved, using 0.25ø or 0.50ø sieve intervals, on a W. S. Tyler Inc. Ro-Tap

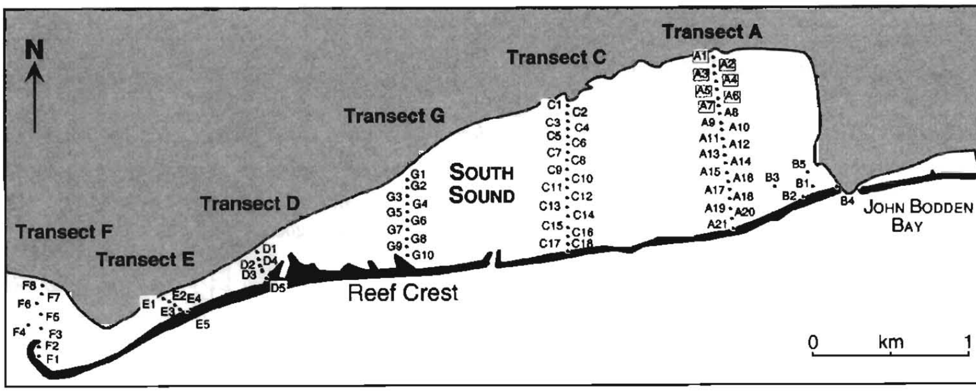

Figure 3. Map of South Sound showing locations of transects, loose sediment samples, cores, grid surveys, and rubble measurements.

Shaker, Model RX-29, using the W. S. Tyler Canadian Standard Sieve Series.

Equations used for calculating statistical parameters follow FOLK (1966, 1968), FOLK and WARD (1957), and BOGGS (1995). The mean, sorting, and skewness were determined from the plotted cumulative probability percentage graphs. The mode was determined from the highest peak on a histogram.

The mean diameter of each rubble piece was calculated by dividing the total length, width, and height by three. The shape of each cobble is based on ZINGG's (1935) classification.

Compositional Analysis

Thin sections were made from loose sediment samples, selected sediment samples from the cores, and sieved grain size fractions. The sediment was embedded in blue epoxy and mounted on standard glass slides. At least 150 grains from each thin section were identified and point-counted following procedures described in ROBERTS (1976).

RESULTS

Surface Facies of South Sound

The facies are based on their biota, sedimentary components, grain size, and location. The *Thalassia* (seagrass) Facies, Sand Facies, and Rock Bottom Facies are widespread. The Rubble Facies, Coral Head Facies, and Brown Algae facies have a more restricted distribution.

Thalassia Facies

This facies is found along the shore from 5 m to as far as 380 m into the lagoon (Figure 4). Isolated banks and large

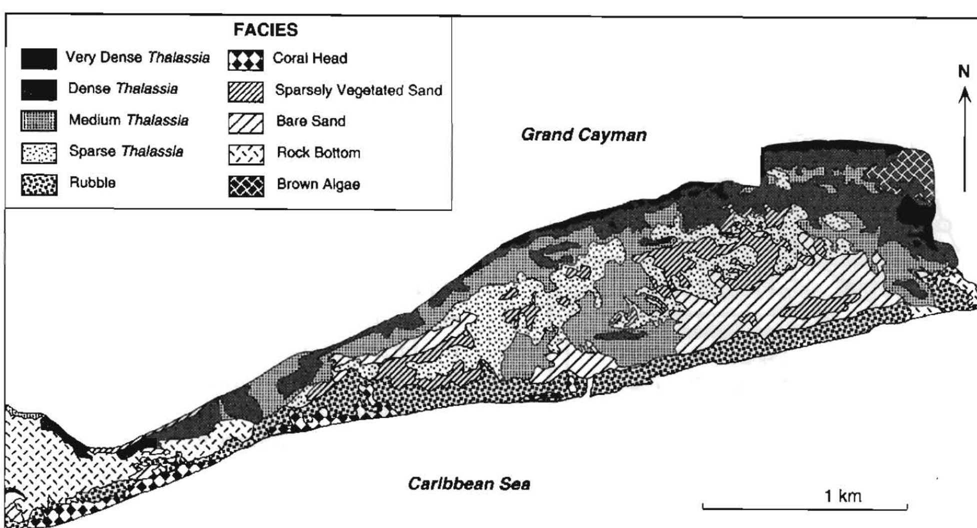

Figure 4. Simplified facies map of South Sound derived from color digital facies map (BEANISH, 2000, fig. 3,1; BEANISH *et al., in press,* fig. 1) produced by image analysis of air photographs taken in 1992.

Table 1. *Composition of the very dense, dense, medium, and sparse* Thalassia *facies. For biota: VR = very rare; R = rare; C = common; VC = very common.*

Facies Plants/m²	Tone on Air Photos	Biota	Position in South Sound	Grain Size Min	Grain Size Mean	Grain Size Max	Dominant Sediment Components
Very Dense *Thalassia* >2000	Darkest	*Thalassia tesudinum* (VC), *Tedania* (C), *Siderastrea siderea* (C), *Halimeda* sp. (C)	Discontinuous thin band along shore, eastern part	N/A	2.3	N/A	Mollusks 41% *Halimeda* 21% Forams 17%
Dense *Thalassia* 500–2000	Dark	*Thalassia tesudinum* (VC), *Halimeda* sp. (R), *Tedania* (C), *Porites porites* (R), *Siderastrea radians* (R), *Siderastrea siderea* (R), *Favia fragrum* (R)	Parallel to shoreline along length of lagoon	1.9	1.2	1.0	Mollusks 52% *Halimeda* 29% Forams 9%
Medium *Thalassia* 250–500	Medium	*Thalassia tesudinum* (VC), *Syrigodium filiforme* (R), Halimeda sp. (R), Penicillus dumentosis (C), *Caulepra cupressoides* (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* (R), *Siderastrea radians* (R), *Favia fragrum* (R)	Scattered patches throughout lagoon from shore to reef crest	2.4	1.5	0.5	Mollusks 54% *Halimeda* 26% Forams 9%
Sparse *Thalassia* <250	Medium to Light	*Thalassia tesudinum* (VC), *Syrigodium filiforme* (R), *Halimeda* sp. (R), *Penicillus dumentosis* (C), *Caulepra cupressoides* (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* (R), *Siderastrea radians* (R), *Favia fragrum* (R)	Fringes sparsely vegetated sand facies on landward side	1.9	1.2	0.6	Mollusks 67% *Halimeda* 10% Forams 9%

Thalassia patches are, however, found adjacent to the Rubble Facies, within 60 m of the reef crest. The *Thalassia* Facies is 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 1). The Very Dense *Thalassia* Facies (> 2000 plants/m²) and the Dense *Thalassia* Facies (500–2000 plants/m²) have plants with long, wide blades. In the Medium (250–500 plants/m²) and the Sparse (< 250 plants/m²) *Thalassia* Facies the leaves tend to be shorter and thinner. The Medium *Thalassia* Facies is the most widespread *Thalassia* Facies in South Sound.

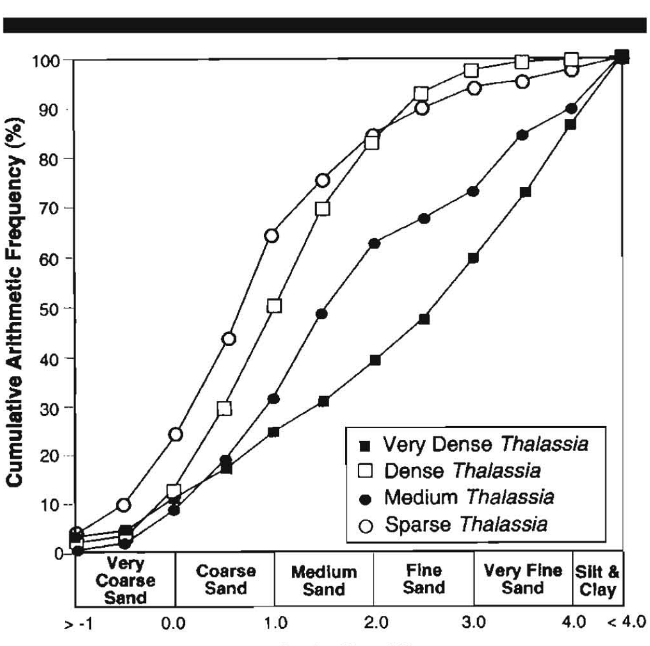

Figure 5. Graphical comparison of the grain size in the Very Dense, Dense, Medium, and Sparse *Thalassia* facies.

The surface sediment of the *Thalassia* Facies is a poorly sorted medium skeletal sand (Table 1). Mean grain size decreases from medium sand to fine sand shoreward as *Thalassia* becomes progressively denser (Figure 5). The sediment in the Medium *Thalassia* Facies is slightly finer-grained than the Sparse and Dense *Thalassia* Facies. Sorting becomes poorer as *Thalassia* density increases. The sand is formed of mollusk fragments, *Halimeda* plates, benthic and planktonic foraminifera, red algae, and coral fragments (Figure 6). The Very Dense *Thalassia* Facies has the largest percentage (13.3%) of silt and clay in the lagoon. The bivalve and red algae grains are extensively bored and micritized whereas the foraminifera show minimal alteration. Overall, grains in the *Thalassia* facies have moderate micritization and low boring (Table 2). In general, the grain size distribution is not related to grain composition.

Thalassia testudinum forms 85–99% of the vegetation in the Very Dense and Dense *Thalassia* Facies (Table 1). The Medium and Sparse *Thalassia* Facies include scattered *Syringodium filiforme* along with green, brown, and red algae.

Porites porites, Siderastrea radians, Favia fragrum, Tedania, and unidentified brown chimney and orange massive

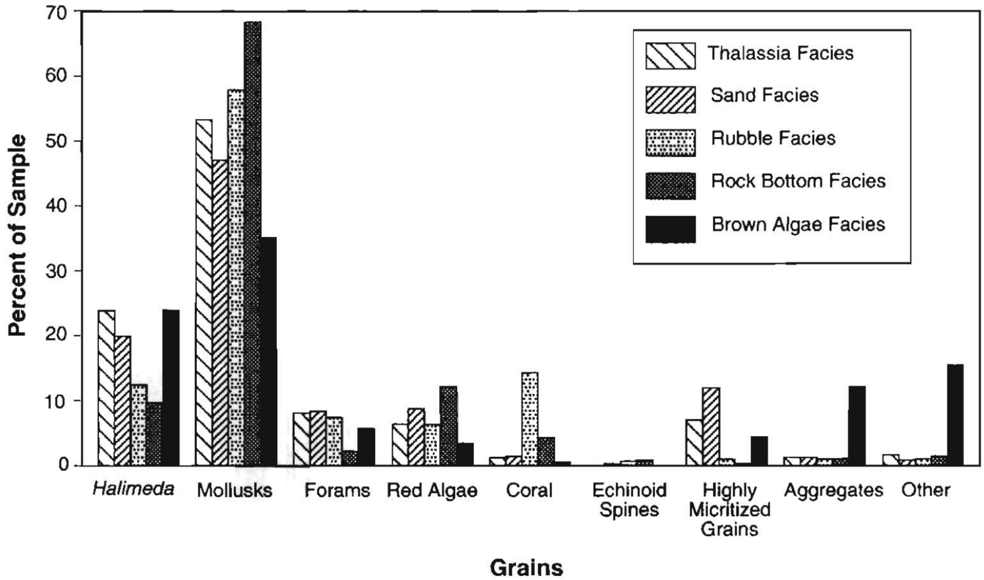

Figure 6. Graphical comparison of the grain constituents of facies found in South Sound.

sponges, (Table 1) can tolerate the temperature and salinity changes and the high sedimentation conditions found in the *Thalassia* Facies. The seagrass community supports a diverse biota (*e.g.*, sea cucumbers, short-spined sea urchin, hydroids, green sea turtle, parrotfish, gastropods including *Strombus gigas* and *S. costatus,* and bivalves) by providing shelter, substrate, and/or food (BEANISH, 2000). Epibionts (encrusting red algae, other coralline algae, foraminifera, serpulid worms) are found on most blades of *Thalassia. Callianassa* mounds (30 cm diameter; 10–20 cm high) are common.

Sand Facies

The Sand Facies is located in the central part of South Sound (Figure 4) where the water is 1.7–2.4 m deep (Figure 1C) and the westward flowing currents are moderately strong. The substrate ranges from the Bare Sand Facies to the Sparsely Vegetated Sand Facies. Ripples in the sand parallel the reef crest.

The Sand Facies is formed of a poorly sorted medium sand with an average grain size of 1.8ø whereas the Sparsely Vegetated Sand Facies has a mean grain size of 1.9ø (Table 2). The sediment is slightly finer than that in the *Thalassia* Facies (Table 2). The sand grains were derived from mollusks, *Halimeda,* benthic and planktonic foraminifera, red algae, and corals (Figure 6). The grains are slightly less micritized than in the *Thalassia* Facies, and usually $< 25\%$ of each grain has been bored. Although composition does not affect grain size distribution, whole *Halimeda* plates are concentrated between $-1.0ø$ and $1.5ø$.

The Sparsely Vegetated Sand Facies is characterized by scattered *Thalassia* and *Syringodium filiforme* along with green algae, bivalves, and gastropods (BEANISH, 2000). *Acropora cervicornis, Siderastrea siderea, Holothuria mexicans* and *Dasyatis americana* are found locally. Stingrays produce depressions in the sand that are 20–30 cm deep and 1–1.5 m in diameter.

Rock Bottom Facies

This facies is located in the channel at the west end where the currents are strongest, and just west of Prospect Point where strong waves wash over the reef crest (Figure 4). Poorly sorted lithoclasts, 0.5–50 cm long, are common. Local depressions, are commonly filled with a moderately sorted coarse skeletal sand (Table 2) that is < 3 cm thick (Figure

Table 2. *Comparison of facies in South Sound, Grand Cayman.*

Facies	Average Clay Content (%)	Grain Size (ø) Min	Mean	Max	Sorting (ø)	Skewness	Degree of Micritization	Degree of Boring
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–sand	0.3	1.5	0.6	−0.3	0.92	−0.07	Low	Moderate
Rubble–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

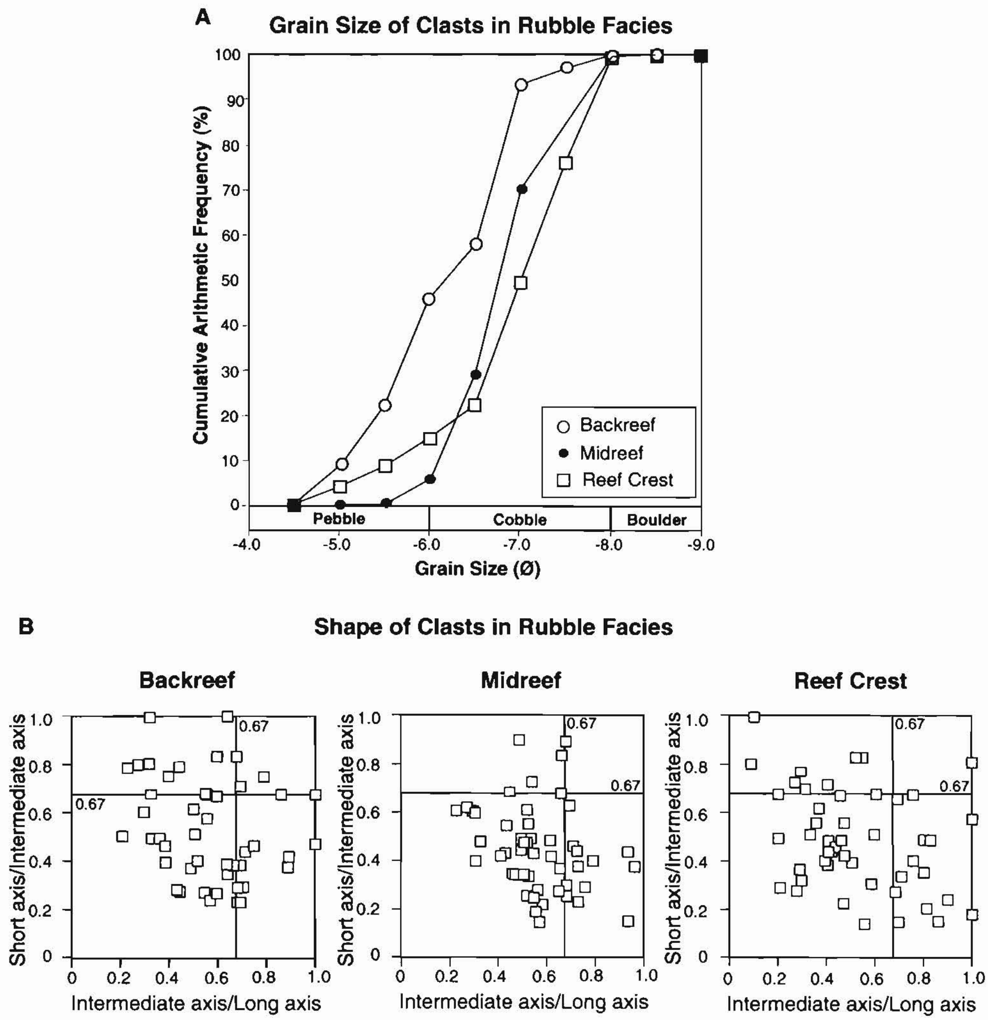

Figure 7. Comparison of the (A) grain size and (B) clast size and shape in the rubble facies found in South Sound.

6). These sediment pockets support the growth of *Thalassia,* various corals, and algae. Various species of green and brown algae attached to the rocky substrates (BEANISH, 2000).

Corals, including *Siderastrea radians, Siderastrea siderea, Diploria* sp., *Acropora cervicornis,* and *Acropora palmata* along with fewer *Poroites astreoides* and *Favia fagrum* are found in this facies. Spiny sea urchins live in crevices in the rock.

Rubble Facies

This facies, a 60–250 m wide zone on the landward side of the reef crest (Figure 4), consists of pebble- to cobble-sized coral rubble that rest on a hard substrate. A thin sediment cover and sediment-filled pockets are common. The smaller coral fragments commonly form the nucleus of rhodoliths. Small patches of Sparse *Thalassia,* Coral Heads, or Bare Sand facies are found locally.

Sediment in the Rubble Facies is formed of coarse sand and cobble-sized material (Table 2). The moderately sorted, slightly negatively skewed coarse sand fraction is formed of grains derived from mollusks, corals, *Halimeda,* foraminifera, and red algae (Figure 6). Its mean grain size varies randomly. The cobble-sized fraction is moderately sorted and near-symmetrical (Table 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 (Figure 7A). There is more cobble-sized material than sand. About 30 m behind the reef crest, the primary grain size decreases to −7.1ø (Figure 7). The amount of sand matrix increases in the backreef area, approximately 70 m behind the reef crest. The midreef zone is moderately well sorted, and sorting decreases to moderate in the backreef and reef crest.

Most cobbles and pebbles are blade-shaped, especially in the midreef area (Figure 7B). Discoid and prolate-shaped clasts are commonly found with bladed clasts in the backreef and reef crest. Spheroidal cobbles are rare. Although most clasts are derived from *Acropora palmata,* the dominant coral at the reef crest, others came from *Montastrea annularis, Di-*

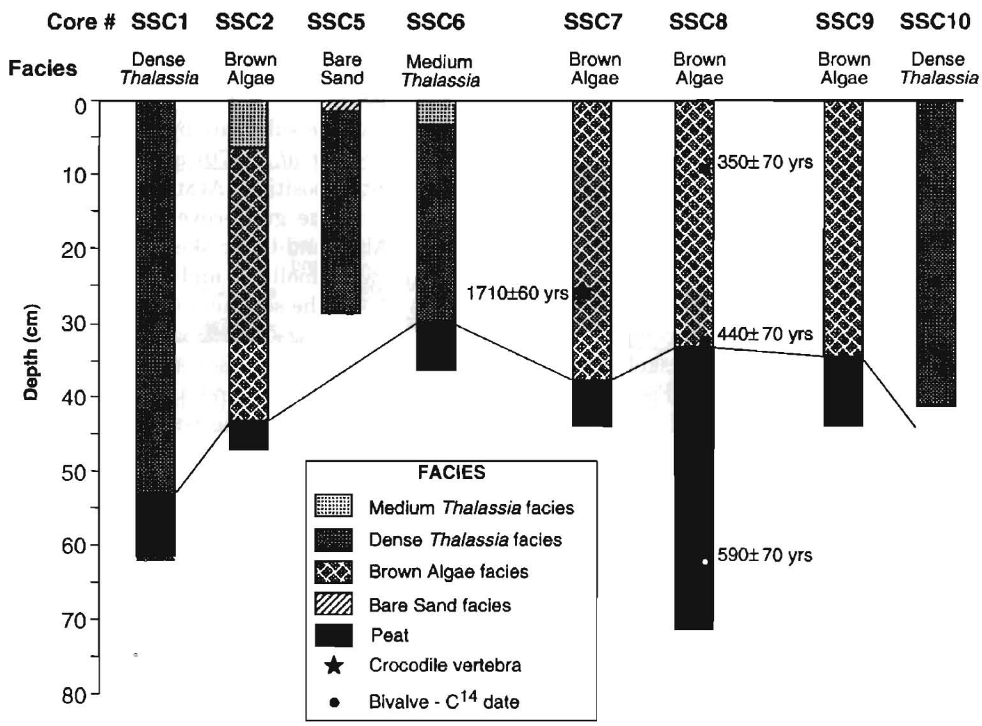

Figure 8. Distribution and correlation of subsurface sediments of South Sound. The ages are based on C^{14} dating of bivalve shells and one crocodile vertebra.

ploria sp., *Acropora cervicornis, Siderastrea* sp., and *Millepora* sp. (BLANCHON *et al.* 1997).

Patch reefs, individual corals, gorgonians, and algae are common in this facies (BEANISH, 2000). *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 creatures living among the rubble include octopi and fire worms. Bioerosion by sea urchins, gastropods, and fish is extensive.

Coral Head Facies

Individual coral heads and coral colonies are common in the Rubble Facies and less common in the Sand Facies (Figure 4). The patch reefs, dominated by *Porites porites, P. astreoides, Acropora palmata, A. cervicornis, Diploria* sp., *Siderastrea siderea, Gorgonia* sp., are 1.2–1.8 m high. *Porolithon pachydermum,* along with other species of coralline algae extensively encrust the reefs. Free-standing corals found on the substrates around the patch reefs include *Siderastrea siderea, S. radians, Montastrea annularis, Agaricia agaricites, Favia fragrum, Millepora squarrosa, M. complanata, Colpophyllia natas,* and *Stephanocoenia mechelinii.* Coral abundance and diversity gradually decrease shoreward of the reef crest.

Brown Algae Facies

This facies, found in the northeast corner of South Sound (Figure 4), is characterized by bare sand *Calianassa* (burrowing shrimp) mounds and algae. Dense red mangroves flank the shoreward margins of this facies. The poorly sorted fine sand includes organic material (*e.g.*, roots) and scattered mollusk fragments (Table 2). Micritization of the grains is low, but most have been moderately bored (Table 2). The surface of the sand is covered by a blanket of unidentified brown algae. Other biota includes algae, small *Siderastrea radians,* and mollusks (BEANISH, 2000).

Core SSC7, taken 6 m from the shoreline in the Brown Algae Facies, contained a crocodile dorsal vertebrae that came from an adult specimen (Figure 8) that cannot be identified (Dr. XIAO-CHUN, Royal Tyrell Museum, per. comm.). Found 26 cm below the sediment surface, it yielded a carbon date of 1710 ± 60 years.

Subsurface Facies Sedimentology and Distribution

Subsurface sediments in South Sound are essentially the same as the surface sediments. Locally, however, there is evidence of facies changes through time. Cores from the Dense *Thalassia* Facies are formed almost entirely of a homogenous skeletal (*Halimeda,* red algae, fragmented mollusks, foraminifera) sand. The deepest core in the Dense *Thalassia* Facies encountered an organic-rich peat with roots at 54 cm (Figure 8). Core SSC6, taken in the Medium *Thalassia* Facies, contains 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 numerous *Thalassia* roots and rhizomes.

Subsurface sediment in the Brown Algae Facies is composed of medium grey, medium- to fine-grained carbonate sand with whole and fragmented *Halimeda* plates, gastropods, and bivalves. A thick black to brown organic-rich peat with structures of vegetal matter lies 34–44 cm below the surface. 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. Cores taken close to 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 (Figure 8).

Core SSC5, located in the Sand Facies, is composed of a tan-coloured, medium-grained, homogenous skeletal sand which represents the Dense *Thalassia* Facies (Figure 8). It is capped by 2 cm of the Bare Sand Facies.

Carbon dating of bivalve shells from core SSC8 shows that the sediments in South Sound are < 590+70 years old (Figure 8). Shells from 9.8 cm, 33 cm, and 62 cm below the surface yielded ages of 350 ± 80 years, 440 ± 70 years, and 590 ± 70 years, respectively (Figure 8). The crocodile vertebra, found 26 cm below the surface in core SSC7, yielded an age of 1710±60 years. That bone, however, was probably reworked from an older deposit. The average sedimentation rate in SSC8 is 1 cm/ 4.5 years. The rate decreased slightly from 1 cm/5.2 years in the lower part of the core to 1 cm/3.9 years in the upper half of the core.

DISCUSSION

Sediment deposition patterns in a shallow lagoon reflect the dynamic interplay between fair-weather and storm controlled processes. Sediment production and dispersal are critical elements that control facies composition and distribution. The former is controlled by the distribution of plants and animals and 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 aperiodic storms. Sedimentological, textural, compositional, and biotic characteristics of most facies in South Sound indicate that currents and waves significantly modified the *in situ,* fair-weather sediments. Only the Rubble Facies is produced and distributed solely by high-energy storms.

During fair-weather periods, most sediment in South Sound is produced by the breakdown of the skeletal components of plants and animals (*cf.,* SWINCHATT, 1965; MAIKLEM, 1968; ALLER and DODGE, 1974; WEFER, 1980; HUDSON, 1985; BAK, 1994; HARNEY *et al.*, 1999). The breakdown of mollusks, green algae, foraminifera, and the epibionts that live on the *Thalassia* leaves are particularly important in this respect (Figure 9A). The resultant sediment typically has a polymodal distribution, with each grain size fraction corresponding to a particular element of the biota. Accordingly, sorting and skewness varies with the local biotic community (SWINCHATT, 1965).

Under fair-weather conditions, low energy and minimal sediment reworking characterize lagoons such as South Sound. Bioturbation and micritization are extensive, whereas fragmentation and mechanical abrasion are low (Table 2). *Thalassia* colonization is uninhibited providing there is a sufficient thickness of sediment in which the plants can root themselves (Figure 9A). Each *Thalassia* plant supports a multitude of epibionts, which will eventually produce mud (STOCKMAN *et al.*, 1967, NELSEN and GINSBURG, 1986). Binding of the substrate by *Thalassia* roots prevents erosion (NEUMANN *et al.*, 1970) and baffling by the blades causes sediment deposition (ALMASI *et al.*, 1987). Preferential deposition in the grass-covered areas leads to bank development. Algal and biotic skeletal grains are common in South Sound with mollusk and *Halimeda* fragments forming at least 65% of the sediment (*cf.,* HILLIS-COLINVAUX, 1980; WEFER, 1980; HUDSON, 1985; MULTER, 1988).

High-energy processes strongly influence sediment distribution in South Sound (Figure 9B). Sediment grain size varies according to 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 of all facies except the Rubble Facies are unimodal, moderately sorted, and do not reflect the structural size of the local biotic community. Grain fragmentation and abrasion are common. These characteristics imply that the sediments were extensively reworked following deposition.

South Sound is located on the exposed windward south coast of Grand Cayman (Figure 2). The dominant northeast trade winds, with an average speed of 5–7 m/sec, almost always have an easterly component (ROBERTS *et al.*, 1975). Those winds generate waves that approach South Sound from the south-southeast. Waves approaching South Sound have a height (< 1 m) and period (6 seconds) that are moderate to low but vary with water depth, wind velocity, duration, and fetch length (VON ARX, 1948; ROBERTS, 1974). Currents in South Sound develop primarily as a response to wind-generated waves breaking over the length of the reef crest, and minor tidal influence

As waves break over the reef crest in South Sound their wave height and intensity are significantly reduced (ROBERTS *et al.*, 1975). The wave-generated surge currents enter the lagoon at a slight angle to the shoreline with an average speed of 10 cm/sec (ROBERTS *et al.*, 1975; SUHAYDA and ROBERTS, 1977). The velocity at which water enters the lagoon is modified by the tides, even though the tidal range of Grand Cayman is only ~ 35 cm. Wave-breaking and set-up are enhanced at low tide when there is less water over the reef (SUHAYDA and ROBERTS, 1977; ROBERTS, 1980). This increases the force with which water enters the backreef area. The circulation in South Sound 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 the water is funneled through the continuously narrowing lagoon (Figure 1C). The currents reach a maximum of 45 cm/sec at the narrowest part of the lagoon, and then begin to slow as the lagoon widens out beyond the reef crest (ROBERTS *et al.*, 1975; DARBYSHIRE *et al.*, 1976; SUHAYDA and ROBERTS, 1977).

Sediment distribution, composition, and texture in South

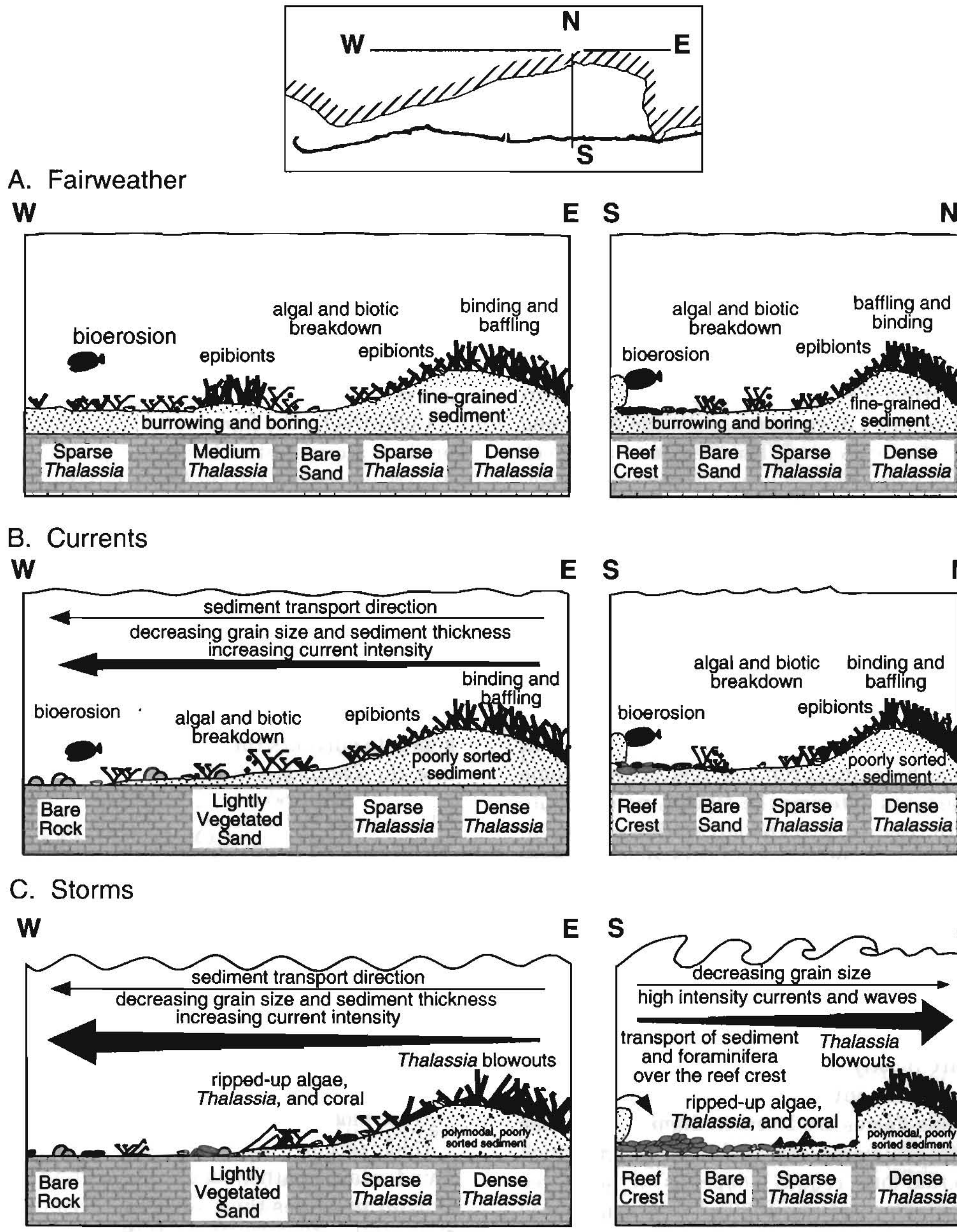

Figure 9. Comparison of processes operative in South Sound during (A) fair-weather, (B) current circulation, and (C) storm conditions.

Sound are related to water circulation in the lagoon. The sediments are thickest where the currents are weakest, and thinnest where currents are strongest (Figures 1D, 9). Sediments in the east part of the lagoon are up to 1.2 m thick; 25–50 cm thick in the central part, and < 5 cm thick on the rocky substrate in the narrow western outlet. In the sheltered northeast corner of South Sound fine sand to clay-sized sediments rich in organics derived from the surrounding mangroves are accumulating. In central South Sound, the sediments are predominantly medium sand-sized. Large unidirectional current ripples, which are normal to the direction of waves entering the lagoon (south-southeast), 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 even under normal current conditions. Currents of 45 cm/sec in the western part of South Sound effectively transport most of the sand-sized sediment out of the lagoon and deposit it on the southwestern shelf (Murray *et al.*, 1977; Roberts and Sneider, 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 are reflected in the patterns and the systematic distribution of the facies. The Brown Algae Facies is found in the northeast corner where almost stagnant waters allow fine sediments to settle from suspension. The Very Dense and Dense *Thalassia* Facies are situated in long, narrow bands that parallel the shoreline where current energy is low (Figure 4). 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. 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 baffling by the plants is less effective.

South Sound supports a diverse biota despite the high current regime. Robust corals, brown algae, and some green and red algae grow in the highest energy Rubble Facies and Rock Bottom Facies. Brown algae grow in exposed areas where water movement is moderate to strong. *Thalassia* growth is limited to areas sheltered from strong currents.

Hurricanes, which have directly impacted the south coast of Grand Cayman (HIRST, 1910; BLANCHON, 1995; KALBFLEISCH, 1995), cause an increase in wave height and intensity. As a hurricane approaches, water is piled up against the shore. As the storm wanes, rip currents are generated as the water flows out of the lagoon (KALBFLEISCH, 1995; KALBFLEISCH and JONES, 1998). With increasing wave height and intensity, waves breaking over the reef crest become more violent and currents entering the lagoon increase substantially in strength (Figure 9C). The circulation pattern in South Sound is temporarily modified. Strong currents flow along the E-W axis of the lagoon and from the reef to the shore (Figure 9C).

Storms and hurricanes are intense aperiodic events that have a major impact on the sediment and facies distribution in a lagoon (Figure 9C). Storm waves transport coral fragments from the reef into the Rubble Facies belt. Cobbles in the Rubble Facies are mostly composed of *Acropora palmata*, which inherently breaks into long "logs". 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 storm waves and currents were able to transport the coral rubble, which averages 20–30 cm in length, up to 250 m into the lagoon.

The backreef Rubble Facies in South Sound stretches along the length of the reef crest (Figure 4). The largest cobbles are deposited directly behind the reef crest, and gradually decrease in size towards shore, as the currents are attenuated. Some rubble, however, is found along the shoreline (up to 24 cm × 12 cm) and scattered throughout the entire lagoon.

The transport of sand into, within, and out of South Sound is enhanced during a storm (Figure 9C). Sediment transport into the lagoon takes place as sediment-laden high-intensity waves wash over the reef crest. Benthic foraminifera in the backreef and up to 500 m into the lagoon are composed of a mixture of lagoonal and forereef taxa (LI, 1997). The forereef taxa were transported over the reef crest during storms or hurricanes (LI, 1997).

Sediment transport in 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. In a modern lagoon on St. Croix, the transport rate of sediments during hurricanes was increased by eleven times over fair-weather conditions (HUBBARD, 1992).

Storms can have a devastating effect on the biota in a lagoon. Large blowouts of *Thalassia* banks in South Sound, for example, result from storms (*cf.*, NEUMANN *et al.*, 1970, SCOFFIN, 1970). Similarly, corals and coral colonies can be ripped-up and destroyed during storms. Unattached and mangled gorgonians are common in South Sound.

Collectively, the fair-weather, current, and storm processes produce a constantly changing lagoonal environment (Figure 9). Areas covered by *Thalassia* become shallower as the sediment accumulates due to binding and baffling by the plants. This further reduces current speed and will eventually change circulation patterns throughout the lagoon. Changes in the processes and sedimentology will also trigger changes in the biota. More *Thalassia* plants will be able to take root as the surrounding sediment thickens. The entire coverage of South Sound by *Thalassia,* however, has not taken place because its expansion is limited by aperiodic hurricanes, which generate currents that are strong enough to defoliate and uproot the *Thalassia*.

CONCLUSIONS

Evidence from South Sound indicates that not all lagoons retain the quiet-water, fine-grained autochthonous deposits with low faunal diversities and extensive bioturbation that are commonly considered typical of lagoons. The sedimentology of South Sound is 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 in South Sound 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, which enhance the effects of everyday currents, distributed sediment and coral rubble throughout the lagoon.

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