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Sedimentology of Shallow, Hurricane-Affected Lagoons: Grand Cayman, British West Indies

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ABSTRACT

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Frank Sound and Pease Bay are small narrow (~4 km long and <1 km wide) shallow water (1.5–2.0 m average depth) lagoons (<0.5 m deep) located on the exposed-windward margin of south coast of Grand Cayman. Collectively, the Rubble and Knob, Bare Sand, and *Thalassia* and Sand zones form 95–97% of the substrates in these lagoons. The Bare Rock Zone, Coral Knolls, and Shoreline Zone are restricted to small areas in both lagoons. Between 1985 and 1992, the area covered by *Thalassia* expanded by colonizing the Bare Sand Zone.

During fair-weather conditions, onshore wave energy is dampened by the reef. Nevertheless, waves that cross the reef are sufficient to maintain lagoonal circulation and "normal" marine conditions. Under these conditions, there is limited sediment production (*e.g., Thalassia* epibionts, bioerosion, green algae), active bioturbation, and expansion of the *Thalassia* banks. Sediment transportation is minimal. At the height of a hurricane, waves and currents pass over the reef and produce a turbulent sediment laden currents that cross the lagoons. As the current loses energy, deposition produces a sediment wedge that grades from boulders-cobbles near reef crest, to pebbles and coarse sand ~80 m from the reef crest, to fine sand 500–600 m from the reef crest. The sediment is poorly sorted and typically has a unimodal grain size distribution. Silt and clay sized sediment is rare. Skeletal constituents indicate that most sediment originates in the fore-reef and shelf environs. As the storm wanes, water that was piled in the lagoons during the storm starts to drain out through topographically controlled mega-rip currents. These high velocity currents destroy biota, uproot *Thalassia,* and strip sediment to reveal bare rock substrates.

ADDITIONAL INDEX WORDS: *Coral reef, bioturbation, seagrass, coastal environments, grain-size analysis, bottom types.*

INTRODUCTION

Due to their violent nature, most studies concerning hurricanes in coastal environments have focused on their effects rather than their processes (*e.g.,* FLOOD and JELL, 1977; MCKEE, 1959; MAH and STERN, 1985; HARMELIN-VIVIEN and LABOUTE, 1986; BLAIR *et al.,* 1994). HUBBARD's (1992) study of Hurricane Hugo's impact on St. Croix is an exception. He showed that as the hurricane approached, waves piled water on the windward shore. As the storm passed, wind direction changed, wave height dropped, and intense currents then drained the trapped water offshore. Given that the shallow-water coastal environments are affected by the storm-wave energy and the intense late-storm currents, the potential for onshore and/or offshore movement of sediments is high.

Frank Sound and Pease Bay are shallow-water lagoons located on the south coast of Grand Cayman (Figure 1). They are protected from onshore waves and currents during fair-weather conditions by a nearly continuous reef (ROBERTS *et al.,* 1975; ROBERTS, 1988). Hurricanes, however, pass over the island with an average frequency of once every 9.2 years (CLARK 1988). Hurricane waves and currents have the potential to pass over the reef and rapidly rework and redistribute sediment. These processes can quickly destroy sediment and biota distribution patterns that are indicative of the normally placid lagoon. Thus, in studying shallow-water sediments such as these, the question becomes one of deciding if they reflect processes that were operative in the "normal" low energy regimes or the rare short-lived, high energy regimes that are triggered by storms and hurricanes. This investigation provides answers to this question by integrating data on the distribution of facies, long-term temporal changes in the facies, sediment distribution, sediment grain-sizes, sediment composition, and biota. The implications of the study are far-reaching because it shows that most characteristics of lagoon sediments and biota in Frank Sound and Pease Bay reflect the influence of the short-lived storms rather than the "normal" placid conditions.

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SETTING AND PHYSICAL CONDITIONS

Frank Sound is ~4 km long and up to 1 km wide whereas Pease Bay is ~4 km long and up to 0.5 km wide (Figure 2). Each lagoon is flanked by land to the north and a reef to the south. Frank Sound has one break in the reef that has been widened for navigation purposes. Although Pease Bay has no navigable breaks in the reef, its crest is slightly deeper at its east end.

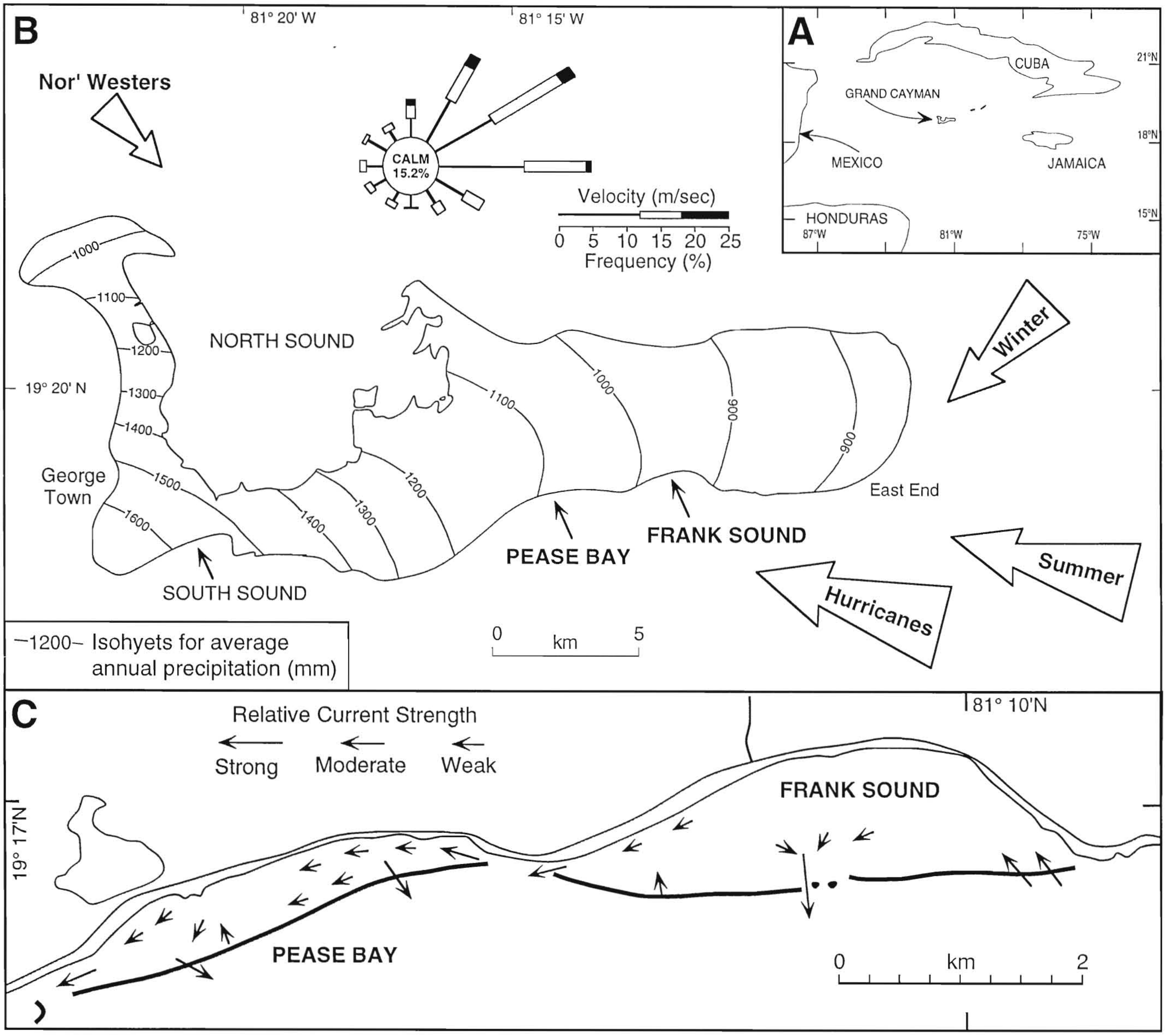

Figure 1. (A) Location of Grand Cayman. (B) Map of Grand Cayman showing wind and storm directions (from DARBYSHIRE *et al.*, 1976), isohyets (mm) of average precipitation (from NG *et al.*, 1992), and location of Frank Sound and Pease Bay. (C) Circulation map for Frank Sound and Pease Bay (from RIGBY and ROBERTS, 1976).

Climate

Grand Cayman enjoys a tropical climate with average daily temperatures of 25.2 °C in winter (Jan.–Feb.) and 28.5 °C in summer (July–Aug.). Winter storms from the NW, however, can produce cold fronts with temperatures of 12.8–15.5 °C (RIGBY and ROBERTS, 1976). Winds, dominated by the easterly Trade Wind belt, average 3–7 m/sec (DARBYSHIRE *et al.*, 1976). During fair-weather conditions, wind direction is from NNE to ESE shifting seasonally from the NW during the winter to E and SE during the summer (Figure 1A). Summer storms approach from the SE.

May to October is the rainy season with the NE part of Grand Cayman receiving less precipitation than the SW (Figure 1B). Frank Sound and Pease Bay are situated between Bodden Town and East End which have average (1986–1993) annual rainfalls of 1241.2 mm and 1208.0 mm, respectively (data collected by Natural Resources, Grand Cayman).

Although hurricane frequency and intensities varies, they pass directly over the island on average once every 10 years (CLARK, 1988). Severe hurricanes crossed the island in 1785, 1836, 1876, 1910, and 1932 (HIRST, 1910; WILLIAMS,

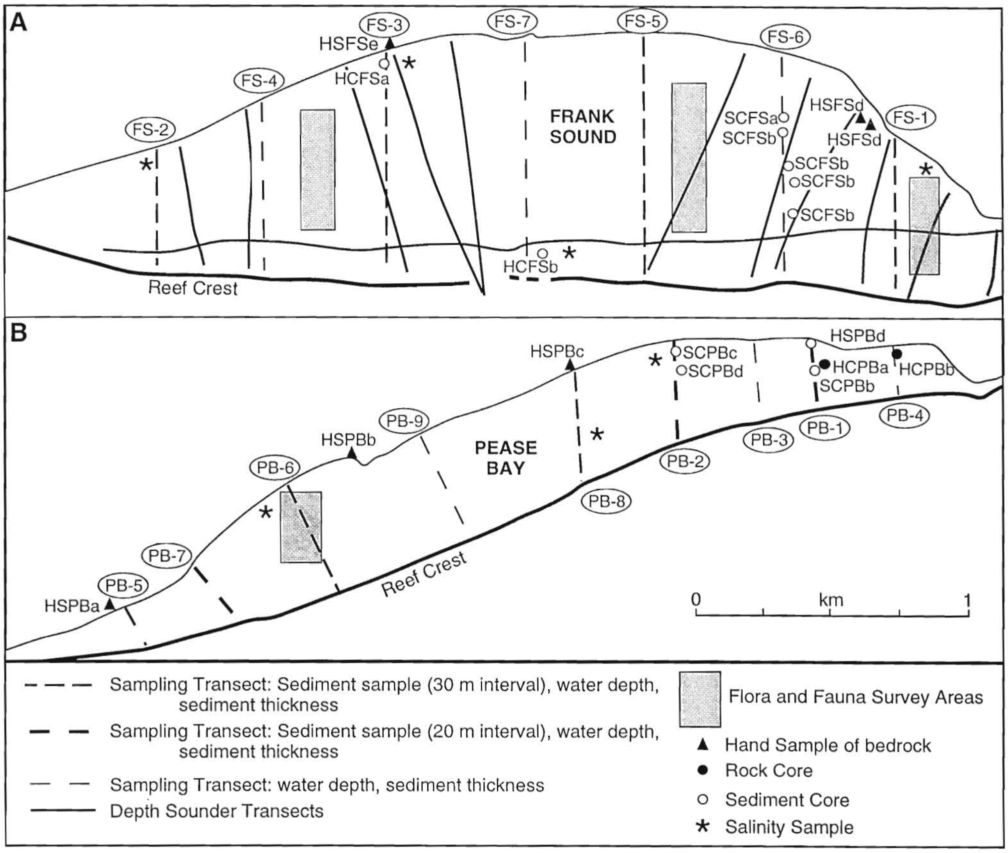

Figure 2. Transect and sample locations in Frank Sound (A) and Pease Bay (B).

1970). Hurricanes from the S or SE have a direct impact on Frank Sound and Pease Bay.

Tides and Waves

Low-amplitude, semi-diurnal tides around Grand Cayman have a strong diurnal component. Tidal amplitude averages 25.8 cm with a maximum of 1.0 m (BURTON, 1994). Primary wave energy is related to the Northeast Trade Winds. The island is protected from high-latitude storm swells originating in the North Atlantic by Cuba and from the South Atlantic by South America and Lesser Antilles. Dominant wave approach changes from the NE during the winter months, to E and SE during the summer months. Wave energy varies over two orders of magnitude between the windward east coast and the leeward west coast (RIGBY and ROBERTS, 1976). Hurricanes, which generally approach from the east, have winds >32.7 m/sec and wave heights >15 m.

Frank Sound and Pease Bay are on the exposed-windward margin where moderate seas (1.25–2.5 m waves) are the norm. Although the reefs dampen onshore wave energy (*cf.* ROBERTS, 1981), less energy is lost (~70%) at high tide when water depth increases over the reef. During the field study, waves in the lagoons were typically <0.50 cm high even though waves were >2.0 m high on the open ocean side. Waves that pass through the central reef channel into Frank Sound reef fan out in an arcuate pattern from the channel opening. During the field study, waves near the channel opening were 0.50–1.00 m high.

Currents

Frank Sound and Pease Bay have a westward circulation due to the collective effects of longshore, strong underset, and tidal currents (Figure 1C). Wind-driven waves generated in the lagoons and remnant wave energy that crosses the reef crest generate the weak westward longshore current. Strong currents develop near breaks in the reef. Waves passing through the channel in the Frank Sound reef produce stronger WSW longshore current along the NW shore of Frank Sound (ROBERTS, 1988). The underset current is driven by the hydraulic head created when onshore waves pile over the reef crest (SUHAYDA and ROBERTS, 1977). At low tide, waves are more completely broken over the reef crest and wave energy is mostly converted into shoreward current energy (SUHAYDA and ROBERTS, 1977).

Temperature, Salinity, and Turbidity

Water temperature is 26 °C (January–March) to 29 °C (June–Oct.) with an average of 28 °C (Water Authority and

Department of the Environment, Grand Cayman). Salinity is 35–38‰ (MOORE, 1973). Salinity in Frank Sound and Pease Bay, which were 36.5‰ during the period of the field work, is relatively constant because there is little freshwater runoff from the land and normal marine water is constantly being added to the lagoons.

Visibility in Frank Sound and Pease Bay, which is generally 10–20 m in undisturbed water, is greatest near the reef crest. Visibility is poorest in the nearshore *Thalassia* grass beds where fine sediment becomes resuspended by wave energy.

METHODS OF STUDY

Field Methods

Nine transects, 150 m to 470 m long, were made in Pease Bay and 7 transects, 470 m to 975 m long, in Frank Sound (Figure 2). Water depth, sediment thickness, and substrate description (*e.g.*, biota, sediment characteristics) were recorded every 10 m along each transect. Salinity was measured at 4 sites in Frank Sound and 3 sites in Pease Bay (Figure 2). Sediment thickness was determined using a probe driven into the sediment by an air powered drill. Other water depths were determined in Frank Sound using a shipboard depth sounder (Figure 2A) (Lowrance X-19) and a Global Positioning System for accurate coordinates (Magellan GPS Nav 5000). A flora and fauna survey for the bare sand and grass substrates was done by counting biota found in a randomly placed 1 × 1 m grids (Figure 2).

Sediment samples (0.5–1 kg) were collected at 30 m intervals along 4 transects in Frank Sound and at 20–30 m intervals along 5 transects in Pease Bay (Figure 2). Sediment cores (4 in Pease Bay, 6 in Frank Sound-Figure 2) were obtained by driving a 10 cm diameter PVC pipe into the sediment (*cf.*, JONES *et al.* 1992). Although the longest core penetrated 97% of the sediment pile, most cores penetrated 60–80% of the sediment pile before being stopped by coarse sediment, boulders, or friction. The PVC pipe was cut and the core split using a thin wire and a knife.

Grain-size Analysis

Grain-size analyses of 71 surface sediment samples and 18 samples from cores were done using procedures described by Folk (1968). Samples with <5% silt and clay were rinsed three times in distilled water and air dried. Samples with >5% silt and clay were left in sample bags without drying. Approximately 20 ml of formaldehyde was added to prevent aggregation and decay during transportation. Although sediment with large amounts of gravel or coarser material (>15%) could not be accurately sampled, the sand matrix was collected for comparison with other areas. The sand fraction was analyzed at 0.25 ø intervals using standard sieves. Silt and clay size distributions were determined using a SediGraph 5100 (v. 3.01). These data were merged using the methods described in COAKLEY and SYVITSKI (1991). Mean and median grain-size, sorting, and skewness were calculated using methods outlined by FOLK and WARD (1957).

Sediment Component Analysis

Thin sections were made from sediment samples by placing different sieve fractions in each cell of a 3 × 5 cell plastic grid, and impregnating with epoxy. Allochem identification relied on comparisons with GINSBURG (1956), PURDY (1962), and ROBERTS (1976), and thin sections of known organisms. Using a microscope, at least 300 grains were identified and counted for each sample.

Substrate Maps

Maps of the lagoon floors were generated by density slicing digital images made from color air photographs and matching those slices to substrates (*cf.*, TONGPENYAI, 1989; TONGPENYAI and JONES, 1991). Colour aerial photographs (1:10,000) taken in April, 1992 were used to compare Pease Bay and Frank Sound. Photographs of Pease Bay (1:50,000), taken in 1985, were used for establishing temporal changes in the substrates.

Digital images were created by scanning air photographs using a Hewlett Packard 2c scanner coupled with Desk Scan II v. 1.51 software (1991–1992). Images scanned in 24-bit colour at 400 × 400 dpi resolution were stored as uncompressed TIFF files. Land, open ocean, and areas present in more than one image were erased using Adobe Photoshop v. 2.5. All further image enhancement and image analysis used Image v. 1.5 on a Apple Macintosh IIfx. Histograms of the number of pixels versus grey-level for Frank Sound and Pease Bay have most pixels in a range narrower than the full 0–255 DN spectrum. Before comparing images, tonal ranges and major boundaries in tone were rendered consistent by clipping and contrast stretching (*cf.* KALBFLEISCH, 1995). Two techniques were used for delineating the facies.

With technique I, DN (Digital Numbers) ranges were assigned to lagoon substrates by analyzing the grey-level histograms, analyzing digital images along sampling transects (Figure 3), and considering substrate distributions shown on published maps. Traverses in Frank Sound and Pease Bay yielded major domains at 1–55 DN, 56–155 DN, 156–205 DN, and 206–254 DN that equate to the beach, bare sand, rubble and knob, bare rock, and *Thalassia* and Sand zones, respectively. This technique is excellent for recognizing the dominant facies. When applied to entire lagoons, however, it was found that (1) there is overlap between substrates; for example, the "beach" substrate is 1–80 DN whereas the "bare sand" is 56–155 DN, and (2) each domain may include more than one substrate type; for example, the 206–254 DN domain includes *Thalassia* beds, gorgonian fields, coral knolls, and bare rock.

Technique II resolves the problem of overlapping tonal ranges by applying density slicing to specific areas in the image. Although the tonal ranges for the Beach and Bare Sand overlap, the former is separated from the latter by *Thalassia*. Therefore, the number of pixels in the 1–80 DN range shoreward of the *Thalassia* give an accurate measure of the Beach. Some substrates (*e.g.*, Coral Knolls-156–255 DN) have a wide tonal range which overlap with other substrates. These have to be manually removed and measured separately. This tech-

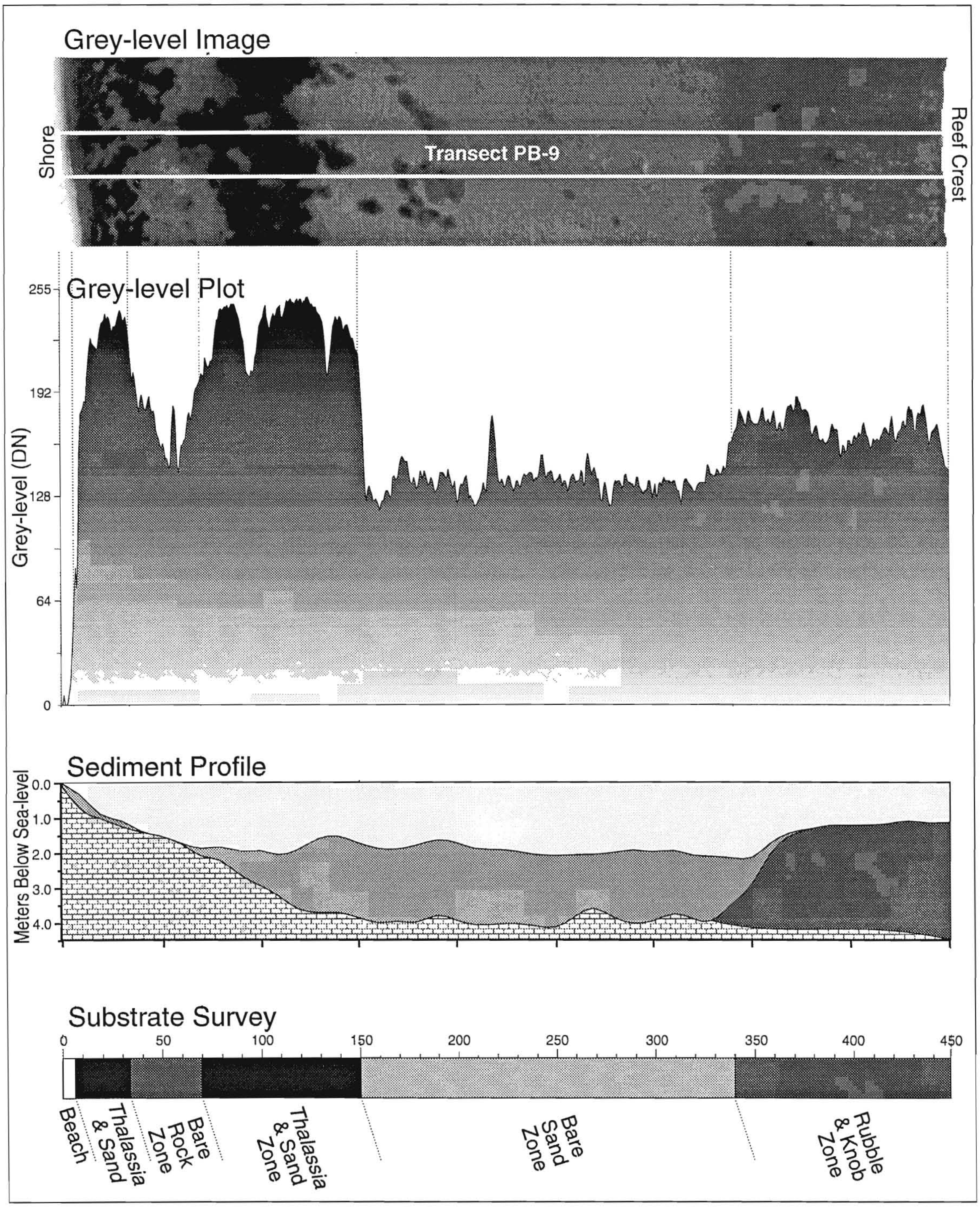

Figure 3. A comparison between the original image's grey-level DN along Transect PB-9 and the substrates recorded during sampling. Comparisons such as these were used to determine classification and in the calculation of error.

nique allows recognition of the Coral Knolls and Transitional Zone.

Technique I was used to delineate temporal facies changes because (1) the dominant substrates are rapidly and consistently determined, (2) fine detail is not needed because temporal changes involve expansion of the *Thalassia* banks, (3) it can be used on older photographs for which ground truthing is impossible and photograph quality is lower, and (4)

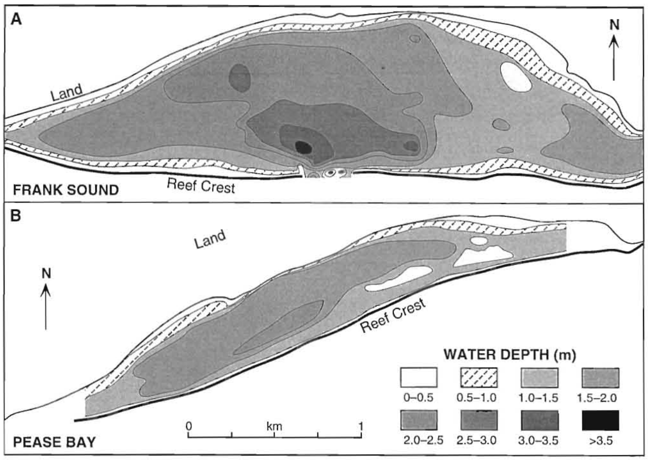

Figure 4. Bathymetry in Frank Sound (A) and Pease Bay (B).

it is equivalent to the method used by TONGPENYAI (1989) and TONGPENYAI and JONES (1991). Technique II is a subjective, time consuming, manual method and the study area must be well known so that the operator can select various features.

RESULTS

Bathymetry

Water depths in Frank Sound increase gradually from the shore to 1.0 m, 100–150 m from the shoreline (Figure 4A). Most of the lagoon has a flat floor in 1.5–2.5 m of water, and is slightly shallower on the flanks and deeper in the central region. Depth gradually decreases across the back-reef to the reef crest and over 100–150 m changes from 1.5 to 0.5 m. Reef crest depth is 0.0–0.5 m and on both sides of the channel opening for ~0.5 km it is generally above sea-level at low tide. The only divergence from this pattern is north of the channel where the lagoon floor is deeper (>2.5 m) and reaches 3.8 m—the maximum depth in Frank Sound.

Pease Bay is shallower than Frank Sound with an average depth of 1.5–2.0 m (Figure 4B). Offshore, water depth increases to 1.5 m, 30 m from shore (Figure 2B; transects PB-8, PB-9). The deepest water (2.15 m) is in the central region. In the east and west thirds of the lagoon the water deepens gradually (Figure 2B; transects PB-1, PB-3). The back-reef area in Pease Bay is variable. The western half of the lagoon has a coral rubble back-reef slope that deepens from 0.5 to 1.5 m over 30–80 m. In the eastern half, the back-reef area has a series of *Thalassia* banks (east-central) and a plateau of cemented rubble (east). Over most of its length, the reef crest is at or near sea-level except at the west (Figure 2B; transect PB-5) and east ends (Figure 2B; transect PB-3) where it is ~0.5 m.

Seaward of the reefs at Frank Sound and Pease Bay, the shelf consists of two terraces that are separated by the mid-shelf scarp (RIGBY and ROBERTS, 1976) that is ~300 m from the reef crest. The upper terrace slopes from the reef (0 m) to the mid-shelf scarp (10 m) (BLANCHON, 1995; BLANCHON and JONES, 1995). The lower terrace, 250–300 m wide, stretches from the base of the mid-shelf scarp (12 m) to the shelf edge (40 m) that is marked by reef growth and an escarpment that plunges nearly vertical to depths of 115–145 m (MESSING, 1987).

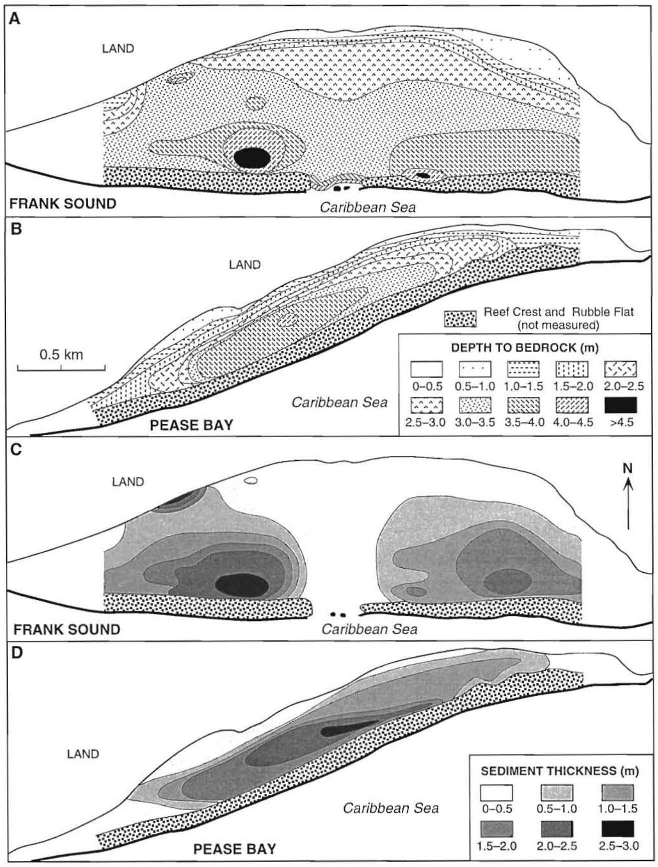

Figure 5. Bedrock topography (A, B) and sediment thickness (C, D) in Frank Sound and Pease Bay. Depths are meters below sea level. The areas immediately behind the reef crest could not be accurately measured because of the nature of the substrate.

Bedrock Topography and Sediment Thickness

The average depth to bedrock is 2.5–3.0 m in Frank Sound and 2.0–2.5 m in Pease Bay. The bedrock surface, however, is uneven with numerous pot-holes (Figs. 5–8) and a few larger depressions with a relief of 1.5–2.0 m. In general, the bedrock surface slopes to >2.0 m below sea-level over the first 50–100 m from shore and then levels off. The greatest measured depth to bedrock in Frank Sound, 4.95 m, is found in a depression northwest of the channel (Figure 5A; transect FS-3). In Pease Bay the deepest bedrock, at 4.2 m, is in center of the lagoon (Figure 5B).

In Frank Sound, major sediment lobes are to the east and west of the channel opening with the thickest accumulations being located over depressions in the bedrock (Figure 5C). The thickest sediment in Frank Sound (3.25 m) is in the west-

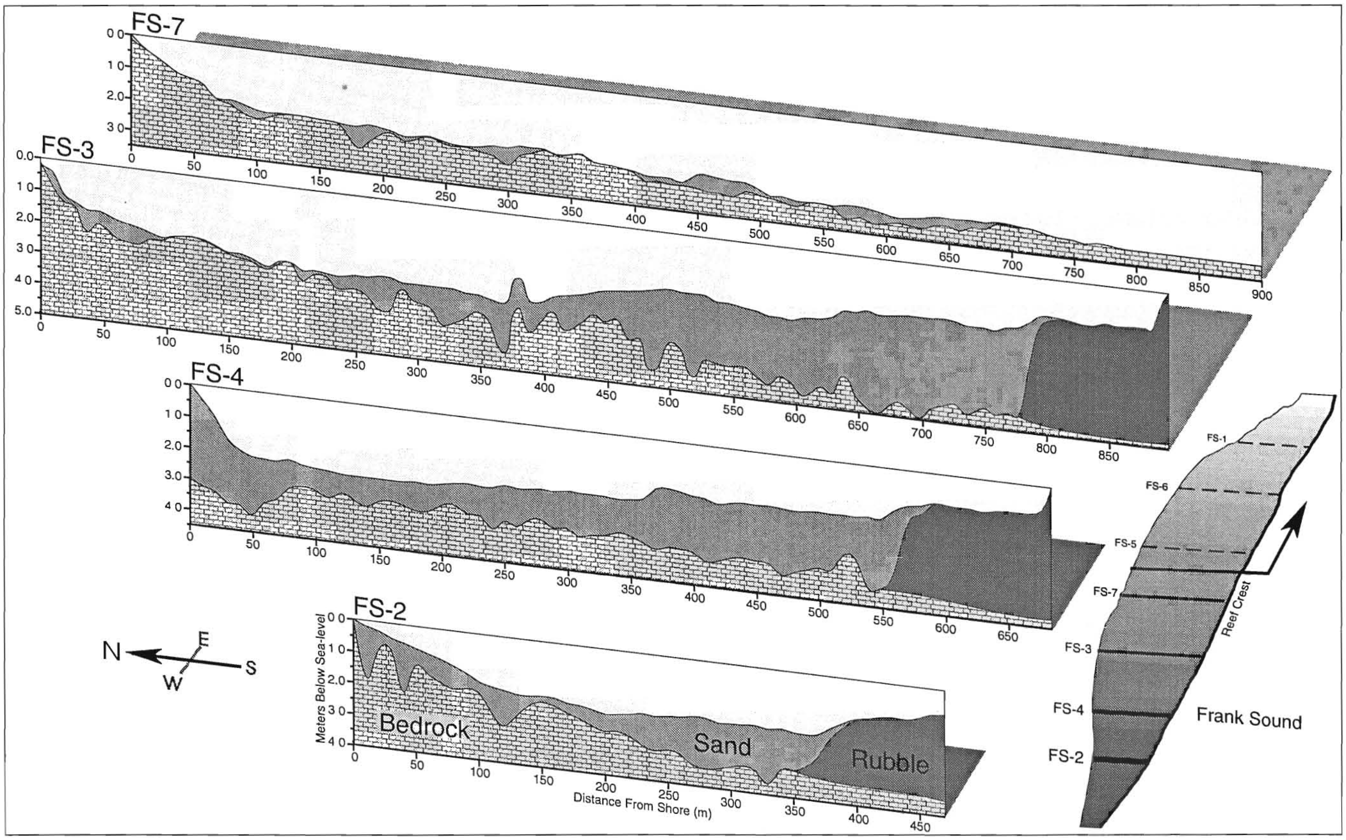

Figure 6. Profiles across four transects in western Frank Sound showing bathymetry, sediment thickness, and bedrock topography.

ern lobe. A smaller lobe located near shore in the west part of the lagoon (Figure 5C) is located over a bedrock depression (Figure 2B). In Pease Bay, average sediment thickness is ~1.0 m with the thickest being (2.5 m) in the center of the lagoon beneath a local rise in the lagoon floor (Figure 5D).

Substrate Zonation

Most substrates in Frank Sound and Pease Bay belong to the Rubble and Knob, Bare Sand, and *Thalassia* and Sand zones (Tables 1–3). The Bare Rock, Coral Knolls, and Shoreline zones collectively form <2% of the lagoon floors (Tables 1, 2).

Rubble and Knob Zone

This 80–120 m zone, located adjacent to the landward side of the reef crest, is a gently-shoreward sloping mass of coral rubble (Figures 9, 10). The area is covered with water 0.5–1.5 m deep, but high points near the reef crest are exposed at low tide. Fair-weather wave energy, broken on the reef crest, is converted into a shoreward moving current. The seaward part of the zone (20–40 m wide) is characterized by turbulence from broken waves and a strong oscillating current with net lagoonward movement. The landward part of the zone is characterized by moderate to strong currents that progressively change direction from lagoonward to westward.

This zone derives its characteristic orange-brown colour from numerous *Padina* sp., *Dictyota* sp., *Stypopdium zonale, Turbinaria* sp., and *Sargassum* sp., *Acanthophora spicifera, Champia* sp., and indeterminate branching red algae that are attached to the rubble. Encrusting *Porolithon pachydermum* locally cement the rubble, especially near the reef crest where currents are strong. Green algae (*e.g., Halimeda tuna* and *Acetabularia*) are present in limited numbers. Robust *Acropora palmata* with thick branches oriented into the wave surge dominate near the reef crest. Coral diversity (up to 25 species) and abundance decreases landward from the reef crest, and domal, and encrusting forms become dominant. *Montastrea annularis* dominates along with *Siderastrea siderea, S. radians, Diploria strigosa, D. labyrinthiformis, Colpophyllia natas, Porites astreoides,* and *P. porite.* Gorgonians, sponges, bryzoans, and hydrocorals live with the corals. *Millepora alcicornis* is found lagoonward whereas the more robust *Millepora complanata* and *M. squarrosa* live near the reef crest. The rubble is extensively bored and bioeroded by gastropods, fish, and echinoderms (*Diadema* sp.). Nocturnal creatures dwelling under the rubble include fire worms, brittle stars, and octopi. Encrusting *Homotrema rubrum* are common on the undersides of rubble.

Sediments grade from boulder-cobble sized blocks of broken coral near the reef crest to cobble-pebble sized rubble at its

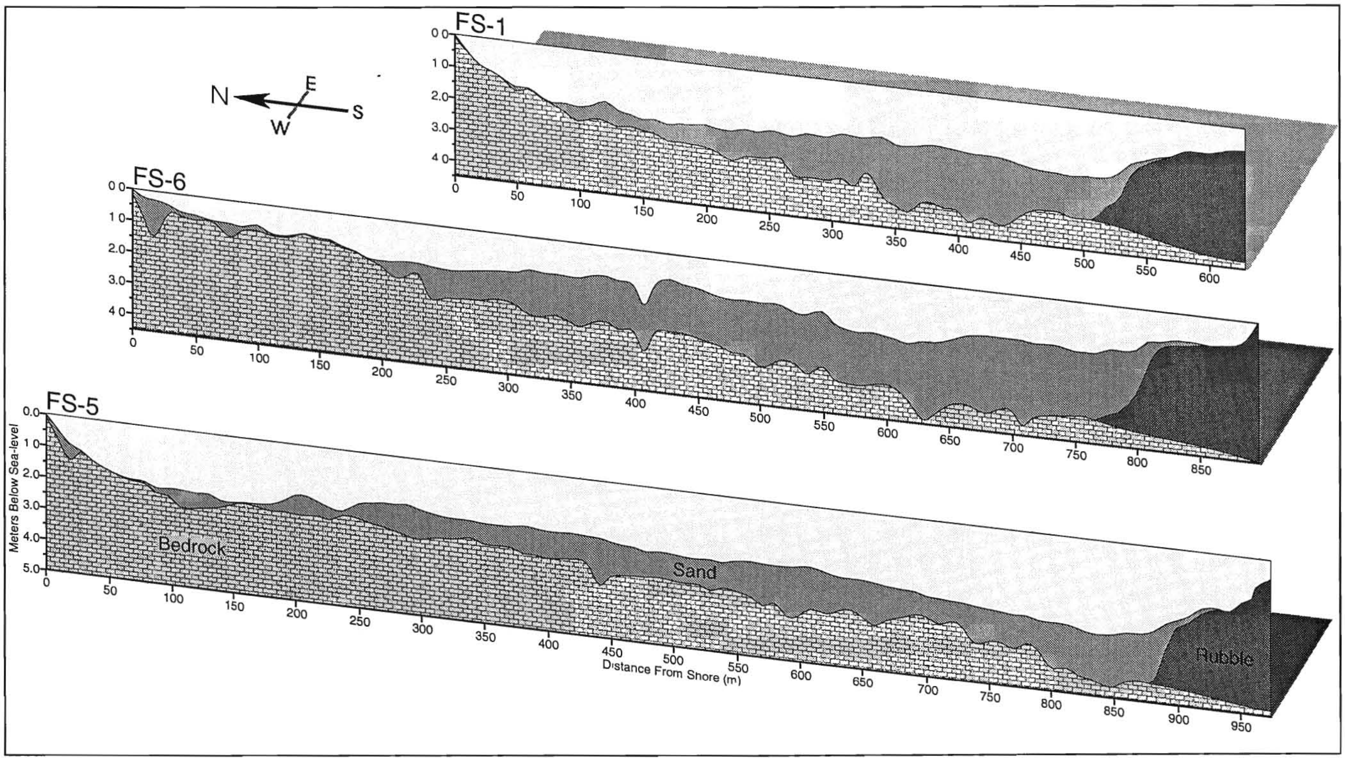

Figure 7. Profiles across three transects in eastern Frank Sound showing bathymetry, sediment thickness, and bedrock topography.

landward edge (Figures 9–11). Sediment at the reef crest has a mean grain-size of −7 ø (medium cobble) with a matrix of pebbles and coarse sand. The sediment is bimodal and moderately sorted with medium cobbles outweighing the matrix sand. 50 m landward of the reef crest, the primary mode is −4 ø (medium pebble). The matrix mode, with a mean of 0–1 ø (coarse sand) is more pronounced. The sediment is very poorly sorted with a strongly fine skewness. Near its landward boundary, 100 m from the reef crest, the poorly sorted sediment is unimodal or weakly bimodal with a mean size of 0–1 ø (coarse sand) and a strong coarse skewness. Sand in the Rubble and Knob Zone is formed of coral fragments (45%), foraminifera (17%), and mollusk fragments (12%) (Figures 11, 12). Fragments of *Homotrema rubrum* constitute over half of the foraminifera. Micritization has rendered many grains unidentifiable (11%).

Bare Sand Zone

This 200–300 m wide zone, located landward of the Rubble & Knob Zone in water 1.5–2.0 m deep (Figures 9, 13), is characterized by barren sand or sand with sparse sea grass and green algae. Currents, which flow shore-parallel and westward, are moderate–low in strength. Pease Bay currents are stronger then those in Frank Sound. Asymmetrical ripples indicate a shoreward current near the Rubble and Knob Zone and a westward current in the interior. Local variations are related to channels, obstructions, and sediment binding plants. Primary sedimentary structures are commonly destroyed by bioturbation.

The biota is dominated by *Halimeda incrassata, H. monile,* and *Penicillus* spp. along with fewer *Avrainvillea* spp., *Udotea* spp., *Caulerpa cupressoides,* and *Acetabularia* spp. Locally, *Thalassia* and *Syringodium filiforme* are common. Sand mounds near the transition with the *Thalassia* and Sand Zone are probably made by *Callianassa or Arenicola* (RIGBY and ROBERTS, 1976). Other organisms include conch (*Strombus gigas*), sea urchins (*Meoma ventricosa, Clypeaster subdepressus*), sea cucumbers (*Holothuria mexicans*), feather duster worms (*Bispira variegata*), and fish. Circular depressions (~20–40 cm deep, 1–1.5 m in diameter) were made by burrowing stingrays (*Dasyatis americana*).

Sediment in this zone is a medium to fine skeletal sand (Figures 9, 13). Mean grain-size changes landward from medium to fine sand or from coarse to medium sand. Sorting decreases from moderate to poorly sorted. Although most sediments in this zone are strongly coarse-skewed, skewness is less negative shoreward. The sediment contains coral fragments (28%), foraminifera (16%), and mollusk fragments (13%) (Figures 12, 13). The high content of coral, coralline red algae (8%), and *H. rubrum* indicates an extra-lagoonal and/or near reef crest source. Micritized grains are nearly twice as common as in the Rubble and Knob Zone. Subsurface sediment are like the surface sediments. Core SCFSf has a mean grain-size of fine sand, moderate-sorting, and strong

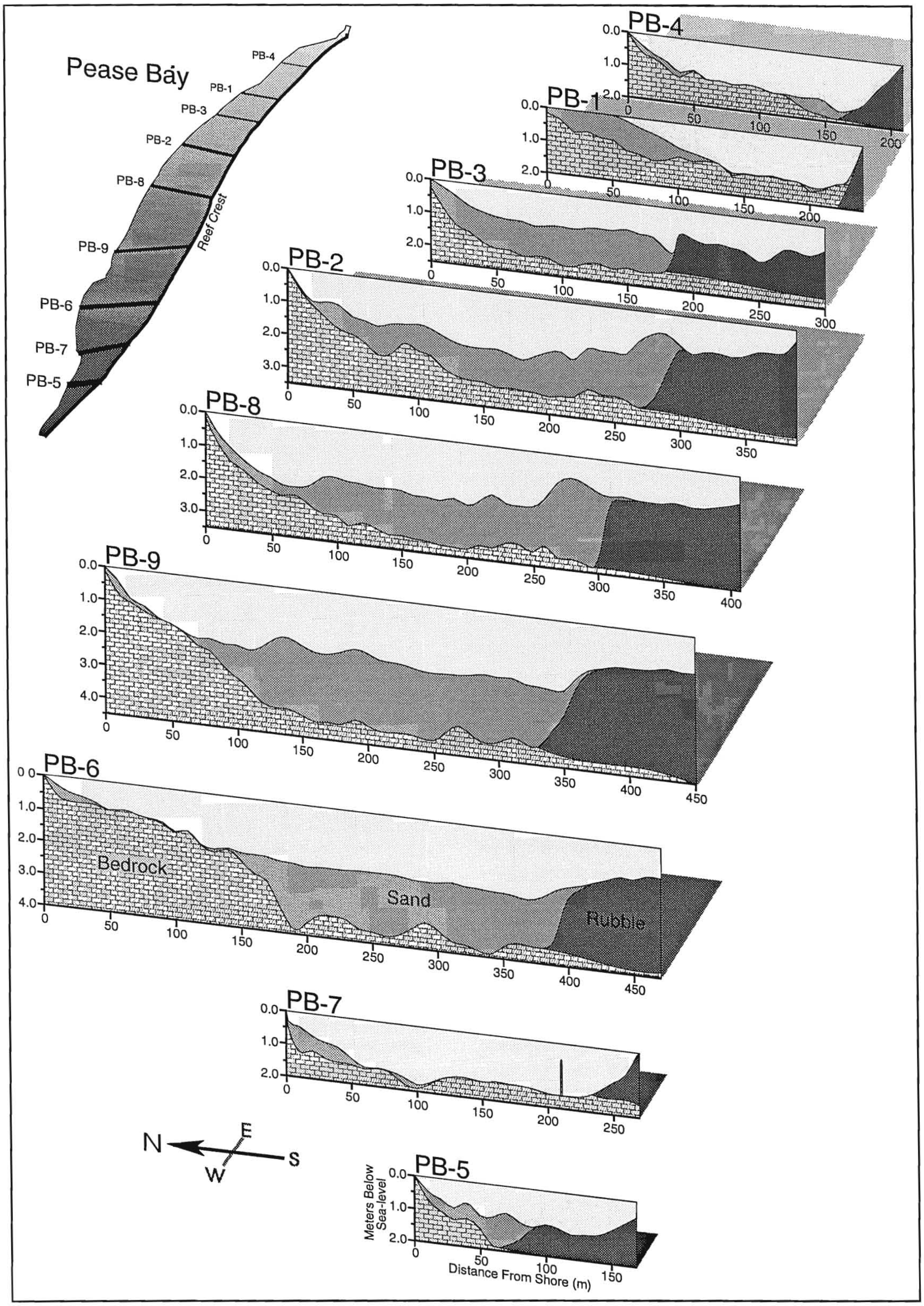

Figure 8. Profiles across nine transects in Pease Bay showing bathymetry, sediment thickness, and bedrock topography.

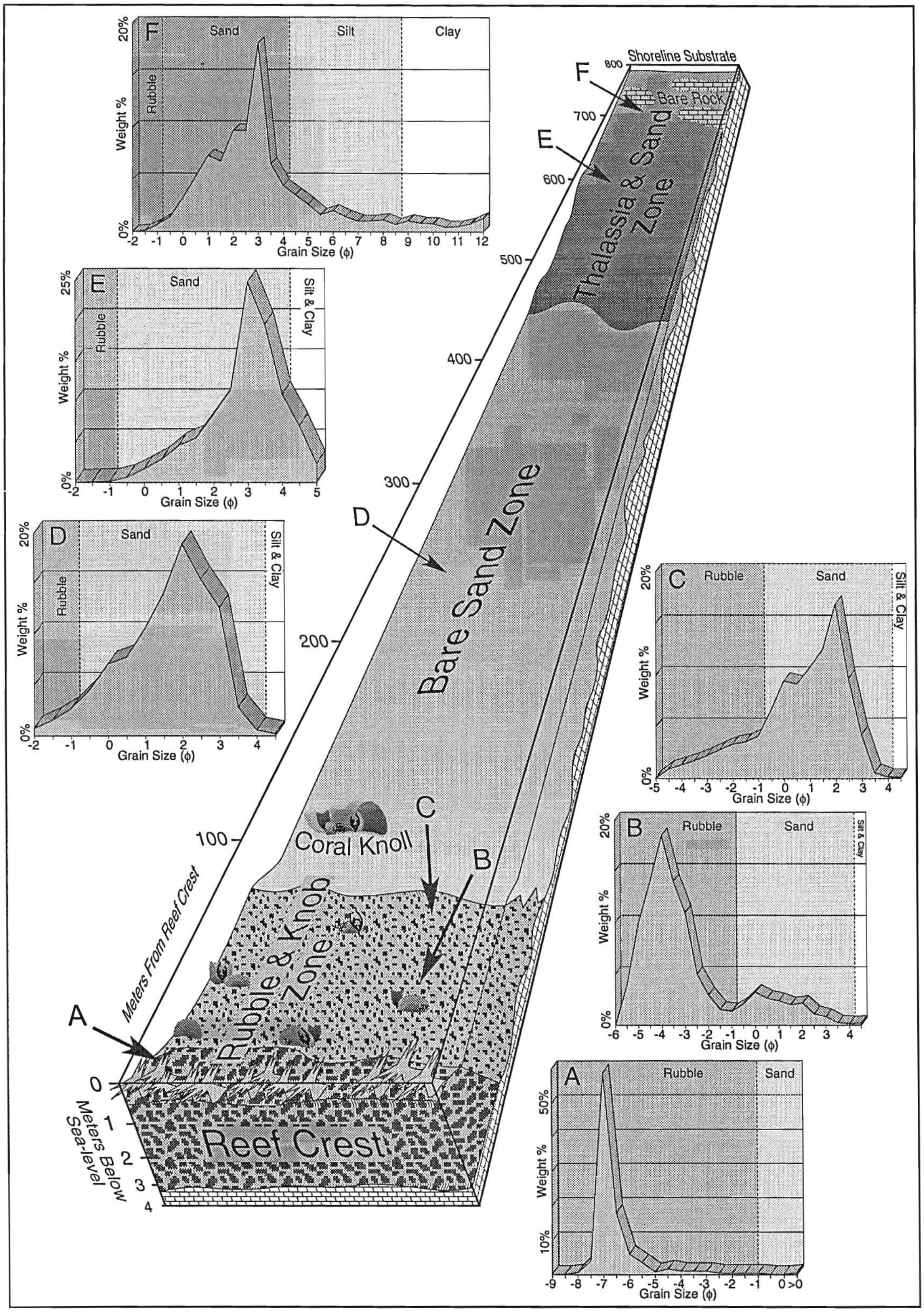

Figure 9. Grain-size variation across a representative lagoon transect. (A–C) Rubble and Knob Zone, (D) Bare-Sand Zone, and (E–F) *Thalassia* and Sand Zone.

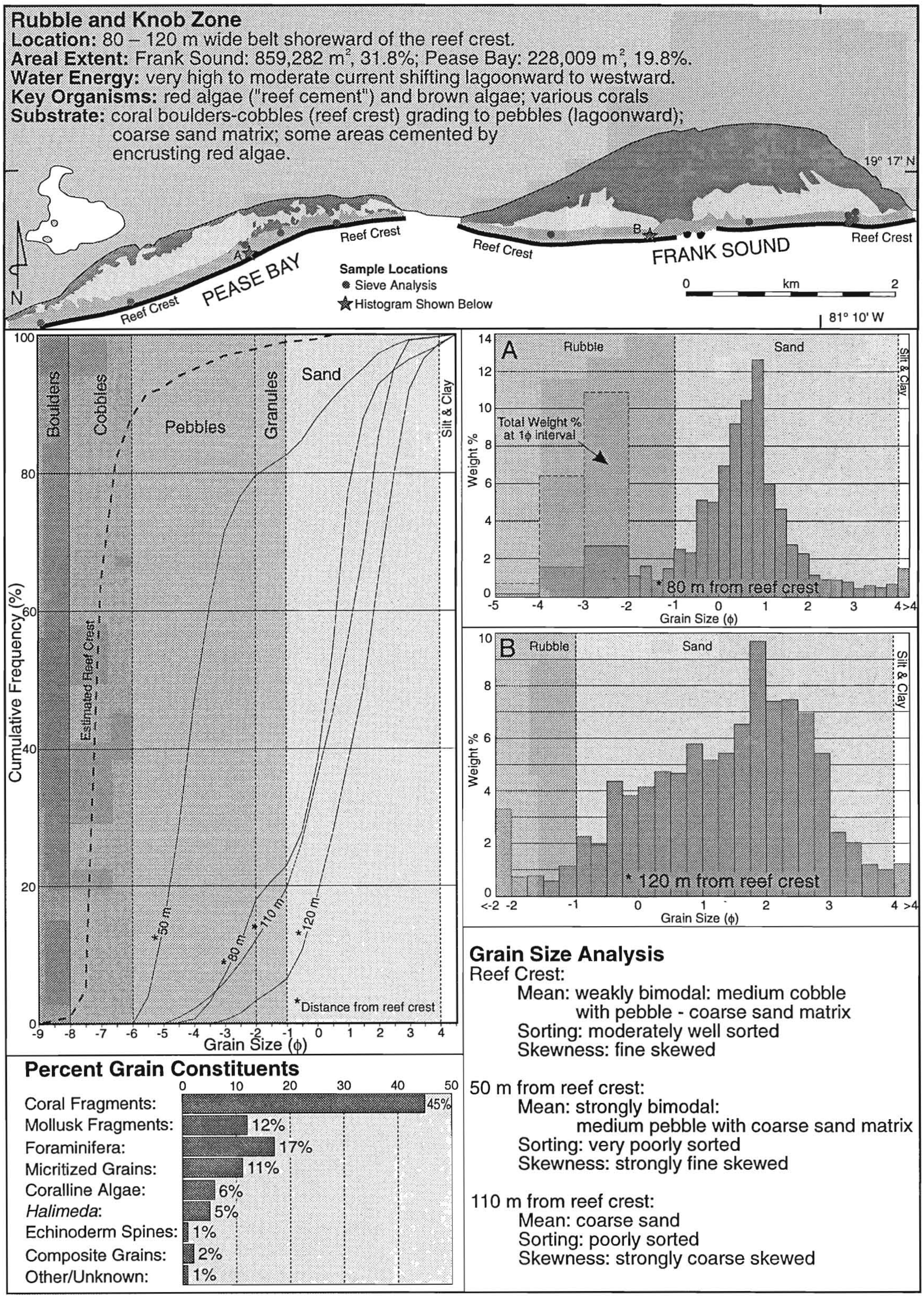

Figure 10. Summary of grain size analyses and constituents in samples from the Rubble and Knob zone.

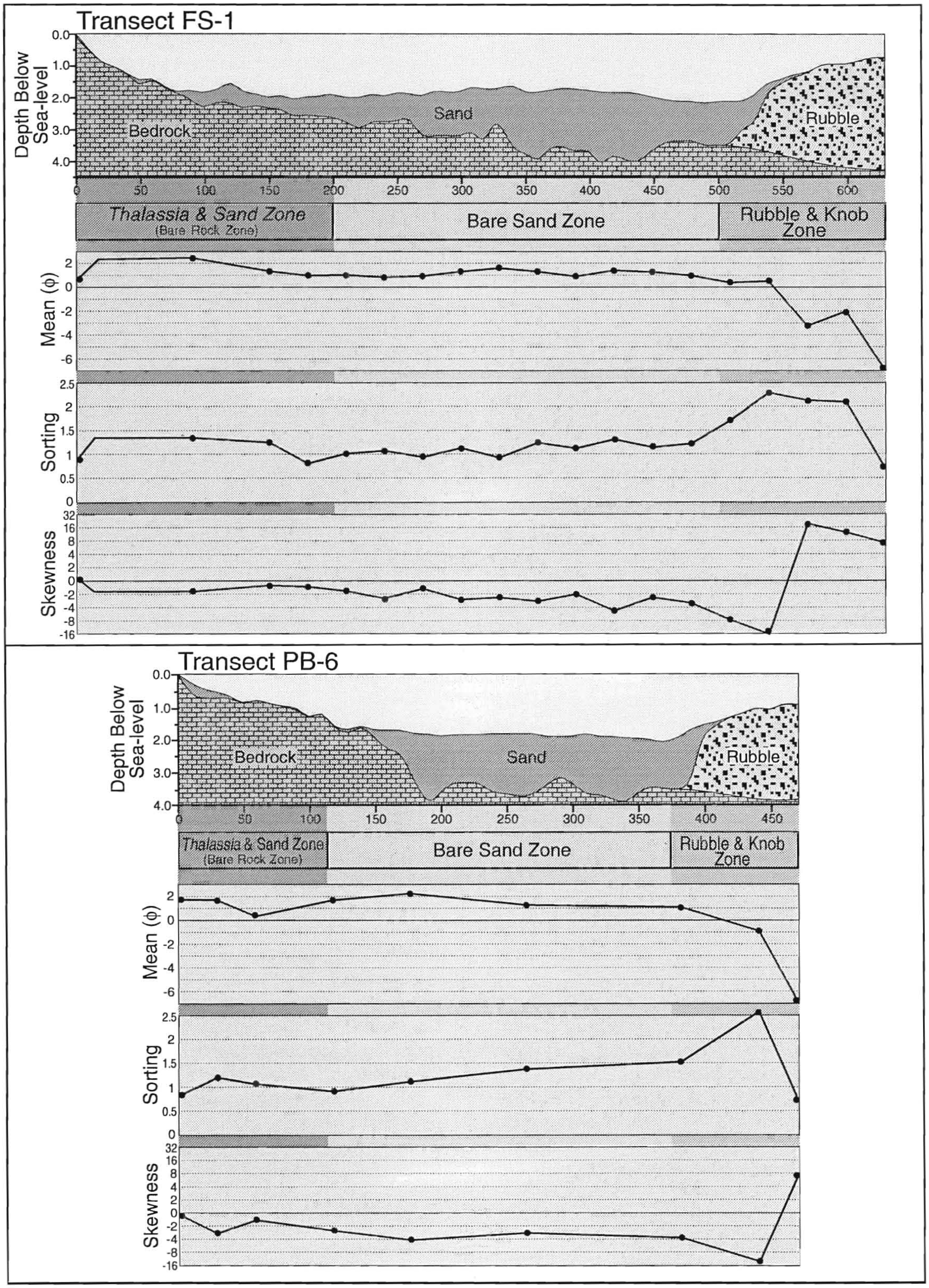

Figure 11. Change in grain-size distribution across transect FS-1 in Frank Sound and PB-6 in Pease Bay.

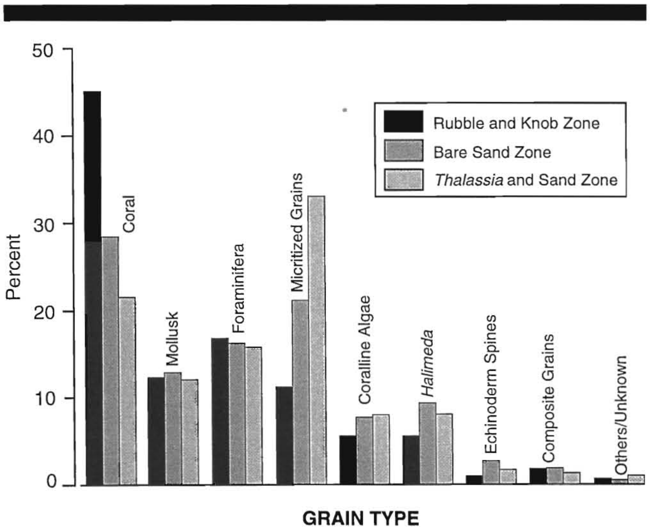

Figure 12. Comparison of grain types in sediment from the Rubble and Knob Zone, Bare Sand Zone, and *Thalassia* and Sand Zone.

coarse skewness down its full length of 134 cm (Figure 14). The entire core consists of clean pink sand, with numerous coral fragments, foraminifera (including *Homotrema rubrum*), mollusk fragments, and *Halimeda.* A layer of pebbles (-3 to -4 ø, coral encrusted by red algae and *H. Rubrum*) are found 40 cm and 50–60 cm below surface in SCFSf and SCFSe, respectively. A coarse layer of shell fragments found 40 cm below the surface in core SCFSd from the transitional zone between the Bare Sand and *Thalassia* and Sand Zones may be equivalent to the pebble layer.

Thalassia and Sand Zone

This zone, landward of the Bare Sand Zone, is characterized by dense *Thalassia* growth in a medium to fine sand (Figure 9, 15). It is divided into the inner and outer parts according to the silt and clay content of the sediment. Isolated *Thalassia* banks are found adjacent to the Rubble and Knob Zone in east Pease Bay. High to moderate currents flow over these banks.

This zone is dominated by *Thalassia testudinum* and numerous green algae (*Halimeda incrassata, H. monile, Penicillus pyriformis, P. capitatus, Avrainvillea nigricans, Udotea flabellum, Caulerpa cupressoides, Acetabularia spp.*) where grass cover is less dense. Brown and red algae, *Syringodium filiforme* and *Halophilia* sp. are found locally. Species that feed directly on *Thalassia* leaves include sea urchins (*Tripneustes ventricosus, Meoma ventricosa*), green turtles (*Chelonia mydas*) and parrotfish (*Sparisoma radians*). Gastropods include *Strombus gigas, S. costatus, Cerithium litteratum,* and *Fasciolaria tulipa.* Bivalves include *Tellina radiata* and *Pinna carnea.* Corals are restricted to small colonies of *Porites divaricata, Siderastrea radians,* and *Favia fragum* (HUNTER, 1993). Conical mounds (typically 30 cm in diameter with a 'crater' on top), like those in the Bare Sand Zone, are common in this zone.

Individual *Thalassia testudinum* have 3–4 leaves (8–12 mm wide, 20–30 cm long) that grow from horizontally spreading rhizomes. Grass density varies from sparse (<100 blades/m^2), to moderate (~100–200 blades/m^2), to dense (>200 blades/m^2). Although 1,000 blades/m^2 was the highest recorded density, 400–500 blades/m^2 was common. The inner *Thalassia* and Sand Zone of Frank Sound had only 2–3 cm of leaf detritus, the maximum for the study area. Broken *Thalassia* leaves seen floating westward in Pease Bay at ~16 cm/sec after a brief summer squall, were continuously being washed onshore. Shore accumulations up to 40 cm thick and 1 m wide were found along the beach at the west end of Frank Sound.

Surface sediment is a medium to fine skeletal sand (Figures 9, 11, 12). Shoreward, mean grain-size decreases and sorting changes from poorly to very poorly sorted. Skewness is negative in the outer *Thalassia* and Sand Zone of Frank Sound and all of Pease Bay. In Frank Sound, sediment in the inner *Thalassia* and Sand Zone is strongly fine skewed. The inner *Thalassia* and Sand Zone of Frank Sound is the only area with significant silt and clay, the maximum recorded was 15% dry weight. Sediment with a silt and clay fraction >10% is rare even in this calm near-shore area. Clay size sediment is very rare. The sediment is composed of coral fragments (21%), foraminifera (15%), and mollusk fragments (12%) (Figures 12, 15). Many grains are unrecognizable because of intense micritization. One sample in this zone, for example, contained ~70% micritized grains.

Subsurface sediments are like surface sediments (Figure 14). Core SCFSa has a mean grain-size of fine-medium sand and poor sorting over its full length. Skewness, however, changes from strongly fine skewed in the *Thalassia* rhizome and root rich upper layer, to strongly coarse skewed below. Organic content is high due to a dense layer of *Thalassia* rhizomes (5–18 cm) and roots down to the bottom of the core (Figure 14).

Oncoids, 2–3 cm long, 1.5–2.2 cm wide, and 1.6 cm high, are common on current swept *Thalassia* banks on the lagoon flanks and near the reef crest in Pease Bay (Jones and Goodbody, 1985). The oncoids are formed of medium and very fine sand.

Sediment binding (*cf.,* NEUMANN *et al.,* 1970), current baffling (*cf.,* ALMASI *et al.,* 1987), and sediment production (*cf.,* NELSEN and GINSBURG, 1986) from epibionts on the *Thalassia,* produced banks in eastern Pease Bay at the edge of the Rubble and Knob Zone that rise ~1 m above the surrounding lagoon floor. Lower banks are found throughout the *Thalassia* and Sand Zone in Pease Bay and eastern and western Frank Sound. Although the *Thalassia* beds are generally resistant to erosion, "blowouts" are present in areas of moderate to high wave energy (*cf.,* NEUMANN *et al.,* 1970). The blowouts are commonly inhabited by green algae, manitee grass, and *Thalassia.*

Bare Rock Zone

This zone of stripped bedrock encompasses pockets of loose sand that are similar in composition and grain-size to that on neighbouring substrates. Areas of exposed bare rock, found nearshore, on the lagoon flanks, and adjacent to Frank Sound channel, experience high energy conditions during

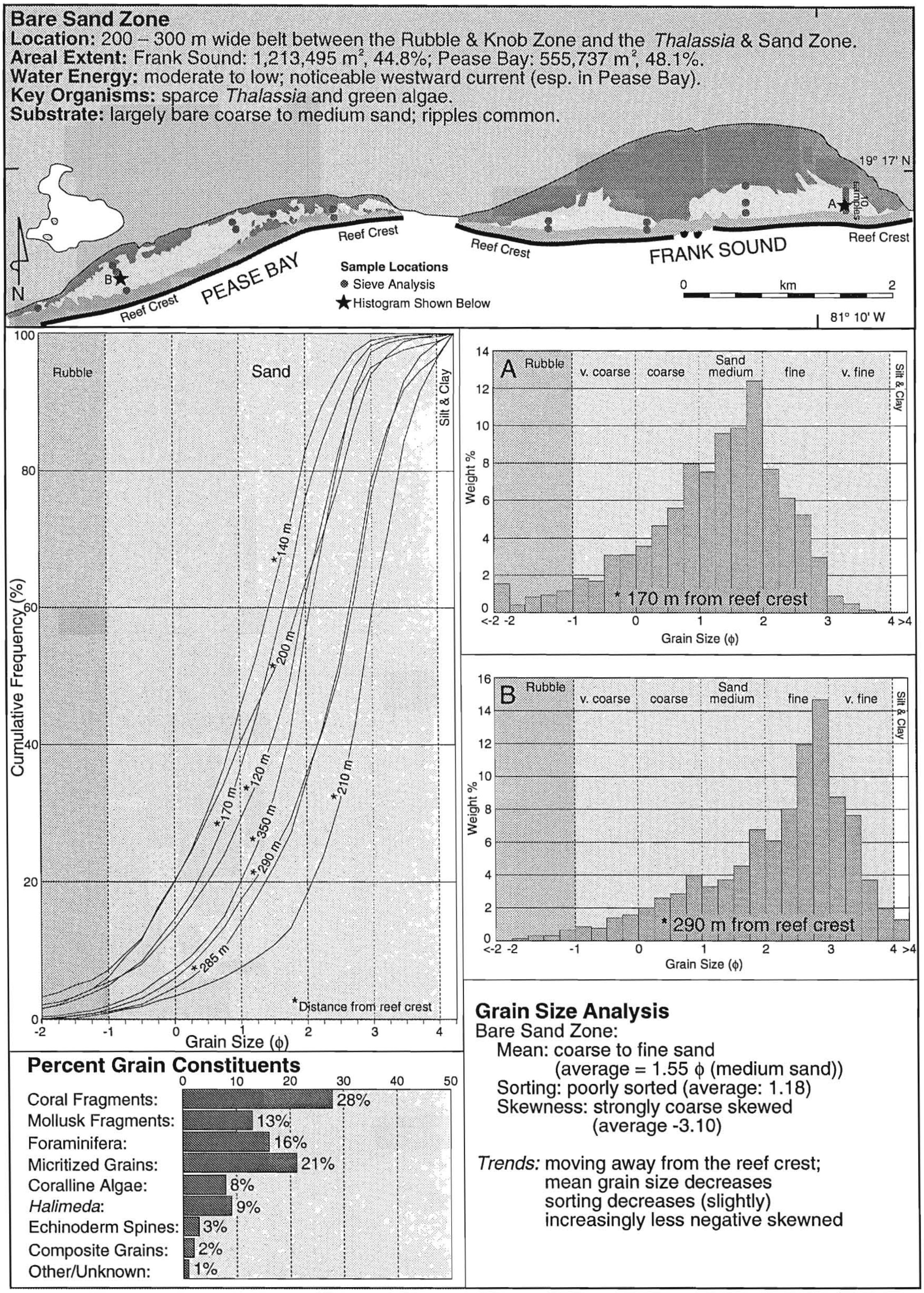

Figure 13. Summary of grain size analyses and constituents in samples from the Bare Sand Zone.

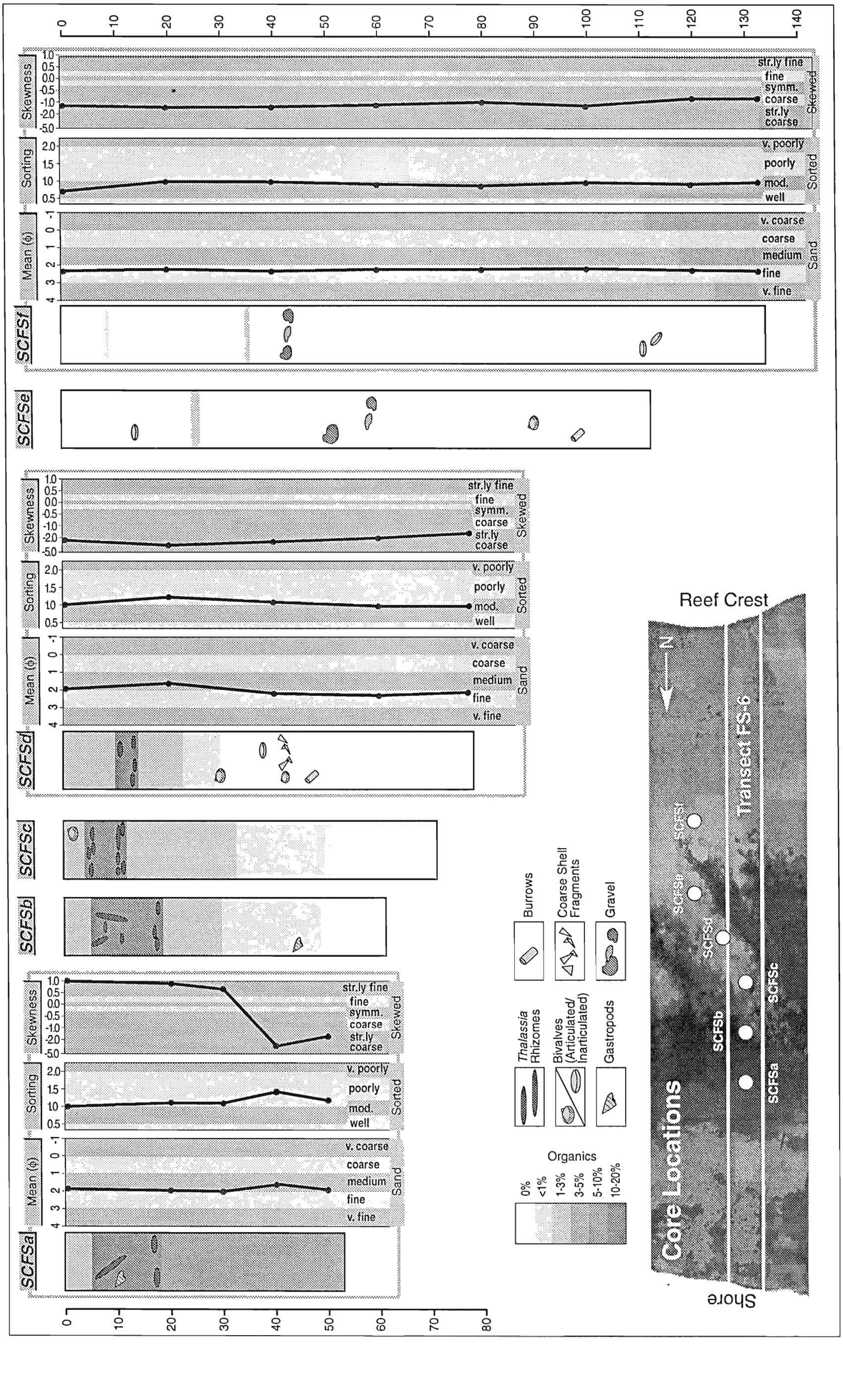

Figure 14. Soft sediment cores from the transition zone between the *Thalassia* and Sand Zone and the Bare Sand Zone on transect FS-6.

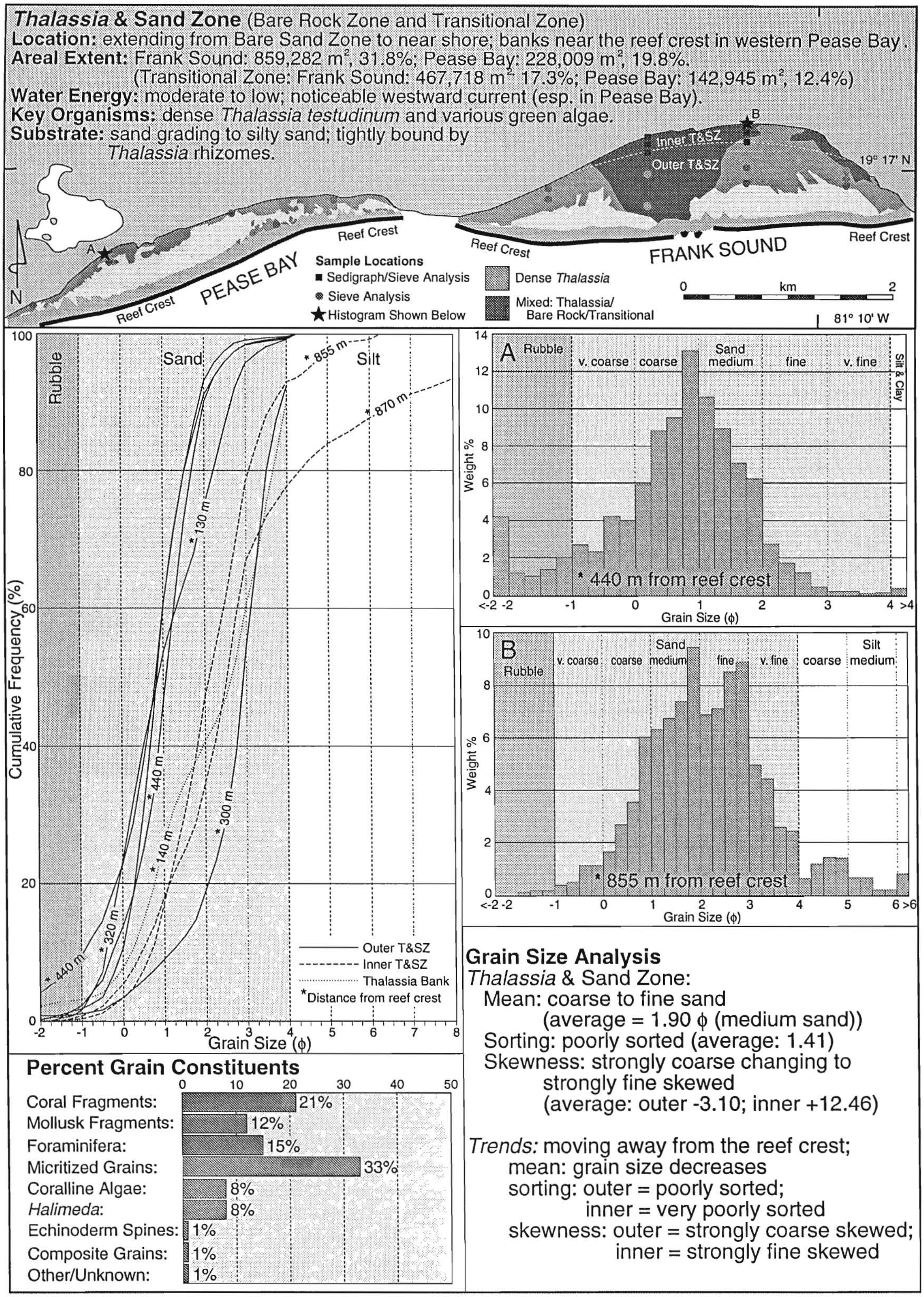

Figure 15. Summary of grain size analyses and constituents in samples from the *Thalassia* and Sand Zone.

Table 1. *Areal extent of substrates in Frank Sound in April 1992 (determined by technique II).*

Substrate	Area DN	West Frank Sound 928,513 m²		Central Frank Sound 814,386 m²		East Frank Sound 963,846 m²		Total Frank Sound 2,706,745 m²	
		Area (m²)	% Area	Area (m²)	% Area	Area (m²)	% Area	Area (m²)	% Area
Beach	0–80	4,130	0.4	2,223	0.3	2,221	0.2	8,574	0.3
Bare Sand	55–155	388,124	41.8	338,127	41.5	487,244	50.6	1,213,495	44.8
Trans/Rock	156–205	160,040	17.2	180,022	22.1	127,656	13.2	467,718	17.3
Rubble Zone	156–205	50,772	5.5	32,209	4.0	46,794	4.9	129,725	4.8
Coral Knoll	156–255	7,619	0.8	19,852	2.4	480	0.0005	27,951	1.0
Thalassia Plain	206–255	317,878	34.3	241.953	29.7	299,451	31.7	859,282	31.8

storms. Nearshore bare rock areas are generally 1.5–2.0 m below sea-level (Figures 6–8). In areas where nearshore bedrock is >2 m below sea-level, thick sediment accumulations support *Thalassia* beds that grow to the shoreline or end abruptly at the beach edge in an undercut scarp similar to a blowout (Figure 2A; transects FS-4, FS-2). The situation is similar on the lagoon flanks. Near the Frank Sound channel opening, the Bare Rock Zone covers a roughly triangular region with its apex at the channel opening (Figure 15). Sediment filled "potholes" are colonized by *Thalassia* whereas areas of higher bedrock lack *Thalassia* and sediment.

Biologic communities in this zone are like those on neighbouring substrates. Nearshore bare rock usually has pockets or a thin veneer of sediment (1–3 cm) with scattered and poorly rooted *Thalassia* and green algae. Small colonies of *Porites divaricata, Siderastrea radians,* and *Favia fragum* are found where sediment is thin or absent (HUNTER, 1993). The lagoon flanks and the area near Frank Sound channel have a more diverse coral assemblage, coral knoll communities, gorgonians, sponges, coralline red algae, and numerous brown algae.

Coral Knolls

Knolls are present in the Bare Rock Zone, Rubble and Knob Zone, Bare Sand Zone, and rarely, the *Thalassia* and Sand Zone. Their need for a hard substrate means that they are most common on bedrock outcrops or stable rubble. The largest (3 m high, 30 m in diameter) and greatest number of knolls are found near the Frank Sound channel. Most knolls, however, are 1–2 m high and <5 m in diameter.

Larger knolls are dominated by large colonies of *Montastrea annularis* and *Siderastrea siderea* along with *Montastrea cavernosa, Diploria strigosa, Porites porites, P. astreoides, Agaricia agaricites* and fewer *Diploria labyrinthiformis, D. clivosa, Acropora cervicornis, A. palmata, Agaricia fragilis, Madracis mirabilis,* and *Siderastrea radians.* Coral diversity decreases as distance from the reef crest increases. Thus, inshore knolls are formed of *Montastrea annularis, Porites porites,* and *P. astreoides.* Gorgonians, sponge, hydrocorals (*e.g., Millepora complanata, M. alcicornis*), green algae (*e.g., Halimeda tuna, Acetabularia* spp.), brown algae (*e.g., Padina* sp., *Dictyota* sp., *Stypopodium zonale*), coralline red algae (*e.g., Galaxaura* sp., *Amphiroa* sp.), and various mollusks live on the coral framework. The knolls shelter numerous fish, lobster, octopi, anemones, and sea urchins (*e.g., Diadema*).

Areas around knolls are characterized by coral fragments, such as pebble size pieces of *Porites,* and are richer in *Halimeda* sand.

Shoreline Substrates

The shorelines along Frank Sound and Pease Bay have a narrow, steep beach that extends <5 m on and off shore from mean sea-level. Bedrock exposures cover long stretches of the shore in eastern Pease Bay, Pease Bay Point, and western Frank Sound. Beach sands are typically medium to coarse grain with an average size of 1.4 ø (medium sand), moderate sorting (0.75 average), and coarse skewness (−0.32 average). Cobble-sized coral rubble is common in areas where the reef crest is nearshore. Beachrock is present at one location in eastern Pease Bay.

Shoreline substrates are inhabited by terrestrial, intertidal, and marine organisms. Burrowing land and marine crabs dominate the beach. The undercut scarps of nearshore *Thalassia* beds are inhabited by crabs and lobster, and schools of young fish are common. The rocky shoreline areas are extensively bored and encrusted.

Distribution and Extent of Lagoon Substrates in 1992

Analysis of the air photographs for Frank Sound and Pease Bay shows that there is a systematic change in the facies across the lagoon. Thus, in a reef crest to shoreline direction, the facies are the Rubble and Knob Zone, the Bare Sand Zone, and the *Thalassia* and Sand Zone (Figure 9; Tables 1–3). This general pattern, however, is disrupted in three areas.

(1) In east Pease Bay, the reef crest is deeper than in the rest of the lagoon (0.8–1.0 m compared to 0.0–0.8 m; Figure 2B, transect PB-3). The strong currents that sweep into eastern Pease Bay (Figure 1C) has produced a series of "spurs" in the back-reef rubble that extend across the lagoon nearly twice as far as the rubble in west Pease Bay. Coral, gorgonians, abundant brown algae, and clean sand patches give the area a mixed and patchy tone on the aerial photographs.
(2) In central Frank Sound, the Bare Sand Zone is absent adjacent to the navigational channel. The lagoon floor from the reef crest to shore is a patchy mix of *Thalassia* and bare rock substrates. This area also contains most of the large Coral Knolls found in Frank Sound.
(3) Where the reef crest converges with the shore on the flanks of Frank Sound and Pease Bay the Sand Plain is absent and Bare Rock Zone dominates. Associated with

Table 2. *Areal extent of substrates in Pease Bay in April 1992 (determined by Technique II).*

Substrate	Area DN	West Pease Bay 682,036 m² Area (m²)	% Area	East Pease Bay 472,548 m² Area (m²)	% Area	Total Pease Bay 1,154,584 m² Area (m²)	% Area
Beach	0–80	4,816	0.7	3,705	0.8	8,521	0.7
Bare Sand	55–155	364,706	53.5	191,031	40.4	555,737	48.1
Trans/Rock	156–205	137,133	20.1	82,239	17.4	219,372	19.0
Rubble Zone	156–205	73,866	10.8	69,079	14.6	142,945	12.4
Coral Knoll	156–255	n/a	n/a	n/a	n/a	n/a	n/a
Thalassia Plain	206–255	101,515	14.9	126,494	26.8	228,009	19.8

the Bare Rock Zone are numerous small Coral Knolls and gorgonians. *Thalassia* banks are found near shore.

Changes in Lagoon Substrate from 1985–1992

Between 1985 and 1992, *Thalassia* coverage in Pease Bay increased by 5.0% of the lagoon area (8,000 m²/year) (Table 3). This conclusion agrees with TONGPENYAI (1989) and TONGPENYAI and JONES (1991) who showed that *Thalassia* coverage has progressively expanded at the expense of the Bare Sand Zone (Table 3). Such changes are comparable to those in South Sound where the *Thalassia* cover expanded by 6.1% of the lagoon area between 1979 and 1985 (TONGPENYAI and JONES, 1991). These numbers indicate that *Thalassia* coverage expands at 0.7–1.0% of the lagoon area per year. Increase in *Thalassia* cover takes place near shore where sparsely populated areas in the *Thalassia* and Sand Zone are being filled in, and by a seaward migration of the seaward boundary of the *Thalassia* banks.

General Trends in Sediment Characteristics

Sediment grades from cobble size rubble near the reef crest to coarse sand at the landward edge of the Rubble and Knob Zone, to coarse sand in the Bare Sand Zone and medium-fine sand in the *Thalassia* and Sand Zone. Silt and clay size sediment is rare apart from a small nearshore area in central Frank Sound. In general, sorting increases from the Rubble and Knob Zone to the *Thalassia* and Sand Zone (Figure 11). Sediment grain-size distribution is Gaussian in nature; polymodal sediment is found in the Rubble and Knob Zone (coral rubble in sand matrix) near the reef crest and in the Inner *Thalassia* and Sand Zone (bioclasts in sand matrix) (Figures 9, 10, 13, 15). Grain composition has no correlation with size distribution in the sand fraction. Most grains were derived from corals, foraminifera, and mollusks.

DISCUSSION

In general, fair-weather waves and currents have little effect on sediment and biota distribution in Frank Sound and Pease Bay. Under those conditions, operative processes include limited sediment production from *Thalassia* epibionts, limited coral growth, foraminifera, and mollusks, bioerosion, bioturbation, and *Thalassia* colonization. During these periods, *Thalassia* rapidly spreads over the Bare Sand Zone and fills sparsely covered areas in the *Thalassia* and Sand Zone. Wave driven water moves over the reef crest (SUHAYDA and ROBERTS, 1977). Water leaves Frank Sound through the channel and, to a lesser extent, out the west end of the lagoon. Pease Bay lacks a major channel, so the excess water is funneled out the west end of the lagoon. Rip currents found at those locations, however, only move small amounts of sediment. Some transportation takes place in the Rubble and Knob Zone, near channels, and from the Bare Sand and *Thalassia* and Sand Zones. Some fine-grain sediment, put into suspension by infaunal activity, is transported out of the lagoons by fair-weather currents.

Fair-weather conditions and processes cannot explain the fact that Frank Sound and Pease Bay are divided into 1) areas of deposition—the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones, and 2) areas of erosion/nondeposition—the Bare Rock Zone. Thus, the possibility that storms and hurricanes control facies architecture must be considered. Although there are no direct observations of hurricane induced current activity in these lagoons, the role of such high energy events can be assessed from the evidence left in the sediments.

Hurricane processes can be divided into the approach and the waning stages. At the peak of the storm, wave height and wave overtopping of the reef crest will be at a maximum (Figure 16). As they pass over the open shelf on the seaward side of the reef, hurricane waves and wind-driven currents en-

Table 3. *Summary of the areal extent of dominant substrates in Pease Bay and the percent change since 1985 (determined by technique I).*

Substrate	Pease Bay Area DN	1985 150,943 m² Area (m²)	% Area	DN	1992 1,154,588 m² Area (m²)	% Area	% Change
Beach	1–25	9,220	0.8	1–55	5,884	0.5	−0.3
Bare Sand	26–105	601,015	52.2	56–155	537,731˙	46.6	−5.6
Rubble/Rock	106–170	273,852	23.8	156–205	285,132	24.7	+0.9
Thalassia Plain	171–205	266,856	23.2	206–255	325,841	28.2	+5.0

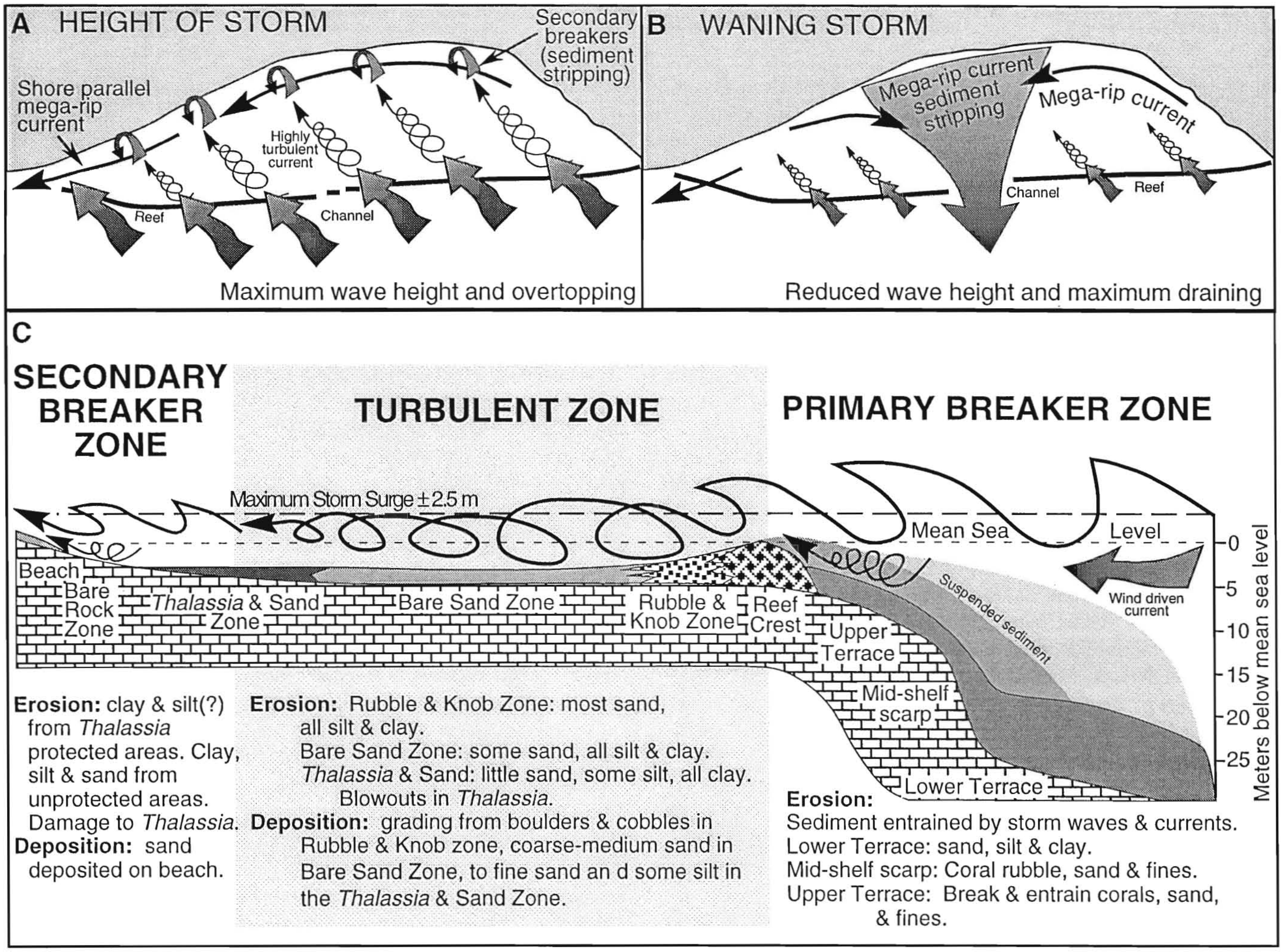

Figure 16. A model of storm waves and currents in Frank Sound and Pease Bay. Map view of Frank Sound at the height of the storm (A) and as the storm wanes (B). (C) Profile across the lagoon and adjacent shelf during a severe storm.

train sediment from various sources (Hernandez-Avila *et al.*, 1977; Jones and Hunter, 1992; Blanchon and Jones, 1995). On reaching the mid-shelf scarp, the abrupt depth change initiates spilling and breaking of the waves that transforms wave energy into a turbulent shoreward current (Figure 16C). This sediment laden current sweeps over the reef crest and as it passes over the shallow lagoon floor, looses energy due to frictional attenuation. As a result, a sediment wedge that grades from the coarsest sediment near the reef crest to finer sediment near shore is deposited. This accounts for the decreasing grain-size across the Rubble and Knob, Bare Sand, and *Thalassia* and Sand Zones, respectively. Fine sediment that accumulated during fair-weather is resuspended and transported shoreward. Wave energy that is not broken over the upper terrace and reef crest area breaks on shore as secondary breakers (Figure 16A). These waves cause nearshore sediment stripping that produces areas of bare bedrock (Figures 6–8).

Under peak storm conditions, the amount of water passing over the reef is orders of magnitude greater than the fair-weather influx. During this stage, the establishment of a return current over the reef is prevented by the strong onshore wind-driven current and high waves. Although some water drains from the western flank of the lagoon (Figure 16A), most water remains piled in the lagoons. During the waning phase of the storm, the wind shifts, and wave height and overtopping of the reef crest decrease. The dominant process during this stage is drainage of the piled water out of the lagoon via topographically controlled mega-rip currents (Figure 16B). The lagoon floor north of Frank Sound channel provides testimony to the extraordinary power of such currents. Up to 300 m north of the channel nearly all sediment has been stripped, and sediment thickness rarely exceeds 0.5 m in the triangular area north of the channel (Figure 15).

Beside a decreasing grain-size trend across the lagoons, several sediment characteristics support the interpretation of storm dominated processes. If the lagoonal sediment was primarily an *in situ* biogenic deposit, the sediment should be polymodal with modes corresponding to the primary breakdown sizes of the contributing organisms. The unimodal grain size distributions in Frank Sound and Pease Bay, however, indicate that physical processes dominate the system. The poorly sorted nature of these sediments also indicates rapid, en masse deposition. Sediment composition points to a depositional system dominated by shoreward transportation. Even in shoreward areas of the *Thalassia* and Sand Zone, the sediment contains high amounts of coral and red algae (Figure 11). Fragments of *Homotrema rubrum,* an encrusting foraminifera typically found on rubble near the reef crest, are found throughout the sediments. Similarly, foraminifera derived from the forereef zone are found throughout the lagoon. Collectively, these observations suggest that most sediment was derived from the reef crest or forereef.

Boulder ramparts, found along the headlands of Half Moon Bay, Breakers, and Pease Bay village, are aligned with the reef crest. As such, they seem to be an onshore continuation of the rubble in the Rubble and Knob Zone. This notion is supported by the similarity in rubble size range and composition in the boulder ramparts and the Rubble and Knob Zone. Rubble near the reef crest has a mean size of medium cobble-small boulder (-7 to -8 ø) with a coarse sand and gravel matrix. Sediment in the boulder ramparts has mean size of -6 to -9 ø with a sorting of 0.5 (well sorted) (RIGBY and ROBERTS, 1976). BLANCHON *et al.* (1997) showed that the rubble behind the reef crests is composed of *Acropora palmata* (57%), *Montastrea annularis* (21%), *Diploria* sp. (10%), and *Acropora cervicornis* (5%) along with fewer *Siderastrea siderea, Montastrea cavernosa, Colpophyllia* sp., and *Millepora* sp. Cobbles and boulders in the ramparts are formed of *Acropora palmata* (51%), *Diploria strigosa* (14%), *Montastrea annularis* (13%), *Diploria clivosa* (6%), and *Montastrea cavernosa* (3%) along with fewer *Diploria labyrinthiformis, Siderastrea siderea, Agaricia* spp., *Acropora cervicornis,* Ironshore rock fragments, and other corals (ROBERTS and MOORE, 1972). The similarity of these deposits indicate that the rubble in the Rubble and Knob Zone and in the Boulder Ramparts were derived from the same source area and emplaced by the same process. Storms or hurricanes are the only processes that have the capability of moving such massive amounts of sediment from an offshore shelf into a lagoon and onto neighbouring headlands.

Absolute data regarding the strength of the currents that move through the lagoons during the various phases of hurricanes and major storms are not available because of the rarity of these events in recent years. Nevertheless, some indication of the current strengths can be inferred by considering the distribution of *Thalassia.* During the interstorm periods about 80% of the lagoon area is quiescent and therefore suitable for *Thalassia* colonization. Extrapolation of past temporal expansions in *Thalassia* distribution in Frank Sound and Pease Bay indicates that *Thalassia* could colonize the Bare Sand Zone in ~70 years if no other controls were operative. *Thalassia* expansion therefore, must be limited by natural forces. Strong currents driven by high waves have the power to uproot *Thalassia:* in March 1975, for example, high waves passed over the reef crest, uprooted *Thalassia* in Bodden Bay (westward extension of Pease Bay) and washed it on shore (RAYMONT *et al.,* 1976). Blowouts, found over 500 m from the reef crest in Frank Sound, are further evidence of breaking waves and strong currents that were able to uproot the *Thalassia* and erode the underlying sediment. Studies conducted elsewhere in the Caribbean and the Bahamas have shown that the current speed required to remove the sand from the rhizomes of sparse, medium, and dense *Thalassia* communities is ~50, ~100, and ~150 cm/sec, respectively (*cf.,* SCOFFIN, 1970; NEUMANN *et al.,* 1970). In Frank Sound and Pease Bay, much of the nearshore *Thalassia,* which is rooted in a thin sediment cover, is characterized by low leaf counts. As such, it is susceptible to storm damage and will probably be defoliated by storm currents and waves (*cf.* RAYMONT *et al.* 1970; SCOFFIN 1970). Comparison with the current speeds derived from other areas suggests that nearshore current in Frank Sound must have been >50 cm/sec in order to defoliate the area. Further from shore, at the boundary between the *Thalassia* and Sand and the Bare Sand Zones, the dense *Thalassia* growth is more stable because it is rooted in thicker sediment deposits. During hurricanes and storms, however, currents in excess of 100–150 cm/sec could uproot the plants and thereby curtail their seaward advance into the Bare Sand Zone. Such currents are easy to envisage because this area is only ~300 m from the reef crest. In the central part of Frank Sound, which is crossed by mega-rip currents that drain storm waters from the lagoon, the high bedrock has little sediment cover and sparse *Thalassia.* Conversely, sediment-filled 'potholes' between the bedrock highs support moderate-dense *Thalassia.* Evidently, the storm currents that drained the lagoon were not strong enough to rip up the *Thalassia* that is rooted in the deeper sediment.

CONCLUSIONS

Storm and hurricane processes greatly exceed fair-weather processes in Frank Sound and Pease Bay. No part of these lagoons escape the effects of the storm processes.

(1) Under fair-weather conditions, sediment production, bioerosion, bioturbation, and *Thalassia* colonization dominate. Although fair-weather lagoon circulation maintains temperature, salinity, and turbidity close to open ocean levels, it does not control sediment or biota distribution.
(2) The lagoons are characterized by the reef-parallel Rubble and Knob, Bare Sand, and *Thalassia* and Sand zones. The Bare Rock Zone is generated by storm erosion.
(3) Depositional processes are controlled by hurricanes. At the peak of a hurricane, waves and currents carrying sediment from the fore-reef environments overtop the reef crest. Once in the lagoons, energy is lost due to frictional attenuation and sediment is deposited. The coarsest material is deposited near the reef crest whereas the finer sediment is transported landward. Their poor sorting and unimodal grain-size distribution indicating rapid deposition.
(4) The Bare Rock Zone results from storm erosion. Storm waves that do not break until they reach the shore, strip sediment from the lagoon floor. As the storm passes, water that was piled in the lagoons, drains out of the lagoon

in topographically controlled mega-rip currents. As a result, areas near channels are stripped of sediment and *Thalassia.*

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

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